ESTIMATING ORGANIC CARBON STOCKS IN SOUTH AFRICAN SOILS

by

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DECLARATION

I declare that the dissertation hereby submitted by me for the degree Magister Scientiae Agriculturae at the University of the Free State, is my own independent work and that I have not previously submitted the same work for a qualification at another University or faculty. I furthermore concede copyright of the dissertation in favour of the University of the Free State.

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DEDICATION

I dedicate this dissertation to my daughter **'NETE 'MACHERE KULEILE.** It was difficult leaving you behind for the past three years my baby, but it was worth it. Thank you for being the best daughter in the whole wide world.

ABSTRACT

The organic carbon stock in South African soils was estimated using existing data with reference to master horizons, diagnostic horizons, soil forms, and land cover classes. The data used for this study was taken from the land type survey which started in 1970 covering the whole of South Africa. Approximately 2 200 modal profiles representing were analysed for physical and chemical properties including organic carbon.

The results showed that the organic carbon content in the master horizons ranged on average from 16% in the O horizon to 0.3% in the C horizons. In the diagnostic horizons, the highest organic carbon was recorded in the topsoils and ranged on average from 21% in the organic O to 1.4% in the orthic A horizons. However, the organic carbon content in the diagnostic subsoil horizons ranged from 1.2% in the podzol B to 0.2% in the dorbank B horizons.

The organic carbon content was related to the soil forming factors namely climate (rainfall, evaporation, and aridity index), topography (terrain morphological units, slope percentage, slope type, and slope aspect) and soil texture (clay). Organic carbon related poorly with climate and topography in both the master and diagnostic horizons, with low correlations. Organic carbon content was positively correlated with rainfall and aridity index in the A, E, B, G, C, and R master horizons and inversely correlated with evaporation in those horizons. Climate had an opposite effect on organic carbon in the O master horizons.

A positive relationship between organic carbon and rainfall was found in the pedocutanic B, prismacutanic B, soft plinthic B, red apedal B, yellow-brown apedal B, red structured B, G, unspecified material with signs of wetness, E, neocarbonate B, neocutanic B, regic sand, stratified alluvium, lithocutanic B, hard rock, unconsolidated material without signs of wetness, unspecified dry material, and saprolite. The relationship between organic carbon and evaporation was negative in those diagnostic horizons. Rainfall and aridity index related negatively with organic carbon content and positively with evaporation in the following diagnostic horizons: soft carbonate B, podzol B, hard plinthic B, saprolite, and the unconsolidated material with signs of wetness.

The relationship between organic carbon and topography was not very clear in both the master and diagnostic horizons. However, topography seemed to influence the formation of some

horizons by restricting their formation to certain slope percentages. The influence of topography on organic carbon content depends on the morphology of the master and diagnostic horizon and underlying material.

A regression was done to study the correlation of organic carbon and the independent variables namely: rainfall, evaporation, slope aspect, aridity index, and clay per master and diagnostic horizon. Unfortunately most of the correlation coefficients were too low for the equations to be used to estimate organic carbon content in South African soils.

Organic carbon in the soil forms behaved as their diagnostic topsoils. The environmental conditions such as water content and temperature that influenced the amount of organic carbon in the topsoils also determined the amount of organic carbon in the diagnostic subsoil horizons of that specific soil form.

Organic carbon stocks were then estimated using three soil bulk density values namely: low = 1.30 g cm^{-3}, average = 1.50 g cm^{-3}, and high 1.70 g cm^{-3}. The results revealed that the organic carbon stocks of South African soils increased from the warmer, drier western to the cooler, wetter eastern parts of the country. The average soil organic carbon stocks is 73 726 kg ha^{-1} when calculated using a soil bulk density of 1.50 g cm^{-3}. Most soils had an organic carbon content between 30 000 kg ha^{-1} and 50 000 kg ha^{-1}. The total organic carbon of the soils of South Africa is estimated to be 8.99 ± 0.10 Pg calculated to a depth of 0.30 m which is 0.57% of the world's carbon stocks. Since the world's carbon stocks were calculated to 1 m depth this is not a true representative value for the carbon stocks of South Africa in relation to the worlds. Therefore a lower value will be expected if carbon stocks are estimated to a depth of 1 m in South Africa.

The organic carbon stocks in the 27 land cover classes ranged from 9 Mg ha^{-1} in barren rock to 120.2 Mg ha^{-1} in forest plantations. The highest accumulation of organic carbon per unit area in South African soils was found in the forests plantations > forests > wetlands. However the biggest contribution to the total organic carbon stocks, was reported in the unimproved grassland> thicket and bushland > shrubland and low Fynbos > forests.

Keywords: organic matter, diagnostic horizon, land cover class, master horizon, soil form.

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CHAPTER 1
INTRODUCTION

1.1 Motivation

Soil organic matter is an important component in earth systems science (Yadav & Malanson, 2007). This has brought about the need for accurate information on the organic carbon content of South African soils at both provincial and national levels. Gregorich *et al.* (2007) discovered that the amount of organic matter in soils varies widely, from less than 1 to 10% (total dry weight) in most agricultural soils. However, most South African soils contain less than 2% organic matter. De Villiers *et al.* (2002) agree that almost 60% of the soils in South Africa have low soil organic matter content, resulting in low soil productivity and high soil degradation. This may be related to the use and management of the soils, which actually influences the accumulation or loss of the organic matter content of soils. This means that the status of organic matter and its indices carbon (C) and nitrogen (N) should be correctly quantified, followed by relevant conservation measures to restore the organic matter resources.

Soil organic matter is composed of many organic substances in various stages of decomposition. Broadly it can be explained as an essential part of the soil that stores and supplies plant nutrients and aids in water infiltration, soil stability, reducing soil erosion as well as balancing atmospheric carbon dioxide (Gregorich *et al.,* 2007). Some soil scientists also think of living plant roots and soil microorganisms as part of soil organic matter (Cooperband, 2002).

Several studies proved that there are several factors that can affect the status of soil organic matter. Many of them originate from human activity. It has become apparent to many people in the world that intensive agricultural systems involving high inputs of chemical fertilizers, synthetic pesticides, hybrid seeds, and mechanical irrigation systems are damaging to soils, crops, and farm workers. These activities contribute highly to the decline in the fertility status of South African soils. This degradation to ecosystems has also been brought about by activities such as deforestation, increased cultivation of marginal lands and overgrazing which consequently lead to loss of biodiversity. The topsoil also becomes more prone to erosion. These activities result in the release of C to the atmosphere. These factors led to a local and international drive to seek alternative agricultural systems that will promote environmental, social, and economically sound food and fibre production.

However, prior to assessing the variations brought about by land use and climate change the present soil carbon stocks have to be estimated (Batjes, 2008). Soil organic carbon estimates have been done by previous researchers. The Soil Survey Staff (1975) reported that the total mass of organic carbon stored in the soils of the world is 1576 Pg of which 32% or 506 Pg was in the tropics. On the other hand later estimates by Post and Mann (1990) indicated that 574 Pg of C are stored in the aboveground vegetation of the world's terrestrial ecosystems. Despite the time difference between 1975 and 1990, the amount of C stored in soils is three times more than what is found in the aboveground biomass (Brady & Weil, 1996). According to Eswaran *et al.* (1993) C in soil is approximately double that in the atmosphere. This authenticates the significance of the soil to the storage of organic carbon. Even though studies such as that of Du Preez (2000) have reported that only 4% of the soils in South Africa contain more than 2% organic carbon and 58% of the soils contain less than 0.5% of organic carbon it would be of great value to actually quantify soil organic carbon contents in South Africa. However, with the major concerns about the "greenhouse effect" this study would interestingly give a picture of the status and contribution of South African soils to the world's soil organic carbon.

1.2 Hypothesis

It is possible to quantify organic carbon stocks in South Africa using existing data.

1.3 Objectives

- The main objective of this study is to quantify organic carbon stocks in South African soils using existing data with reference to master horizons, diagnostic horizons and soil forms in different provinces and for the country.

The sub-objectives are as follows:

- To relate the quantified organic carbon stocks to the soil forming factors climate, vegetation, and topography.

- To estimate the organic carbon stocks in the land cover classes of South Africa.

- To determine the contribution of land use change on the addition of carbon to the atmosphere.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Soil organic matter is considered to be a key attribute of soil quality (Gregorich *et al.,* 1994; Carter, 2002). Doran & Parkin (1994) define soil quality as the capacity of the soil to function within an ecosystem and land use practise, to sustain the biological productivity and maintain environmental quality while promoting the health of plants, animals, and humans. Doran *et al.* (1996) later learned that soil quality is often thought of as an abstract characteristic of soils which cannot be defined because it depends on external factors such as land use and soil management practices, ecosystem and environmental interactions and so on. However, soil quality has actually been typically equated with soil organic matter or its associated indicator elements, namely C and N (Mills & Fey, 2003a, Kotzé, 2004). All soils contain C in the form of organic matter, or humus, the two terms being used synonymously by Stevenson & Cole (1999). Nelson & Sommers (1982) claim that stabilized soil organic matter is approximately 58% C and 5 to 6% N depending on the climate, soil, vegetation, and management practices.

Organic matter or organic carbon is known as the most important parameter within any set of soil analyses for assessing soil quality (Gregorich *et al.,* 1994). Van Antwerpen (2005) found that in all the soil properties that he reviewed, soil organic carbon was undoubtedly the parameter with the most significant impact on soil chemical, physical, and biological properties and is therefore regarded as the most important indicator for soil quality and health. According to Carter (2002) the quality of the soil must be coordinated with a corresponding use or function using best management scenarios. Therefore, soil organic matter can be seen as a relatively stable, integrating soil characteristic that reflects long term land use (Pulleman *et al.,* 2000).

The degradation of dead plant and animal materials in soil is a fundamental biological process because C is recirculated to the atmosphere as carbon dioxide and other associated elements thus making soil organic matter very important in the carbon cycle because a significant part of the C remains behind as soil organic matter and microbial portions (Stevenson & Cole, 1999). Most soil organic matter is present near the soil surface, rather than deeper in the soil. Therefore, maintaining soil organic matter is justified both from an agronomic and a climatic perspective because it affects the capacity of the soil to sustain crop growth (Gerzabek *et al.,* 2006).

Soil organic matter is composed of a series of fractions from very active to very passive. It includes active and inactive organic carbon. Active organic carbon can be easily oxidized and degraded and has significant effects on plants and microorganisms. Active C is considered to be more sensitive than the inactive C to changes in management and land use. Inactive organic carbon represents slowly decomposed soil organic matter and is important to the accumulation and sequestration of carbon (Han *et al.,* 2006).

Well-decomposed organic matter no longer significantly provides as many nutrients for plants and soil microbes as the active pool, but it does play important roles in the soil, such as promoting water and nutrient retention and preventing soil compaction and crusting (Cooperband, 2002). Elementally, soil organic matter is a major terrestrial pool for carbon, nitrogen, oxygen, hydrogen, nitrogen, sulphur, and phosphorus (Doran *et al.,* 1996; Yadav & Malanson, 2007). All these organic constituents of the soil, during various stages of their microbial decomposition, become a source of primary nutrients for soil fauna and flora.

2.2 Status and availability of organic carbon in soil

The organic carbon content of soil varies widely depending on the interaction of a number of factors. These include the factors of soil formation (Jenny, 1941), especially climate and parent material and various other processes of weathering which result in a diverse character of South African soils (Scotney & Dijkhuis, 1990).

There are actually two groups of factors that influence organic matter content: natural factors (climate, parent material, land cover and/or vegetation, and topography) and human induced factors (land use, management, and degradation). The interdepence of these factors on each other as well as their variation contribute immensely to the variability of organic matter in soil (Jones *et al.,* 2004a).

Human activities highly influence the equilibrium of soil organic matter especially land use practices such as cropping both under dry land and under irrigation, stock farming and forestry. However, these agricultural activities either have a positive or a negative impact on the organic matter status of the soil with the latter being the most prominent. Therefore the C content of the soil depends strongly on the type of land cover as well as the land use practices (Arrouays *et al.,* 2001).

The types of land use not only control the magnitude of soil organic carbon stocks, but also influence the composition and quality of organic matter in soils. There are different types of land use practices that differ from region to region. The effect of land use on soil organic matter storage should therefore not only be assessed in terms of total C stocks but also with respect to changes of soil organic carbon structure, stability, and function (Helfrich *et al.*, 2006).

There is currently a shortage of knowledge on the fertility status of South African soils with the primary area of concern being in organic matter content. Fortunately, there have been very interesting developments on the influence of land use change on soil organic matter contents (Scotney & Dijkhuis, 1990) and the distribution of soil organic matter and its indices.

Barnard (2000) did a study on the status of soil organic matter in South Africa. He used data from the land type survey (Land Type Survey Staff, 2003) which started in 1970. Approximately 2380 soil profiles were analysed physically and chemically and used to produce a generalized map for organic carbon in virgin topsoils in South Africa (Figure 2.1). Even though the A horizon is considered to be 0-300 mm the figures used for the study ranged from 50 mm to 1 m in some cases. The organic carbon content of the soils ranged from less than 0.5% to more than 4%. Only 4% of the soils contained more than 2% organic carbon while 58% of the soils contained less than 0.5% organic carbon. The remaining 38% of the soils contained 0.5 to 2% organic matter (Du Preez, 2000). South Africa is therefore characterized by soils with low soil organic matter levels in virgin soils (Scotney & Dijkhuis, 1990).

The organic carbon content of the country also showed an east-west trend (Figure 2.1) in relation to rainfall corresponding with the findings of Alvarez & Lavado (1998) who claimed that the geographical distribution of soil organic carbon follows precipitation trends. There was a very high correlation between mean annual rainfall and carbon content in South Africa. The top soils used in that study relied heavily on annual rainfall, probably because rainfall plays a very important role in determining plant growth and thus biomass production in a specific area. In general the distribution of soil organic carbon follows the same pattern as the rainfall of South Africa. Soil carbon content is negatively correlated with maximum temperature as it breaks down slower in cooler areas (Barnard, 2000).

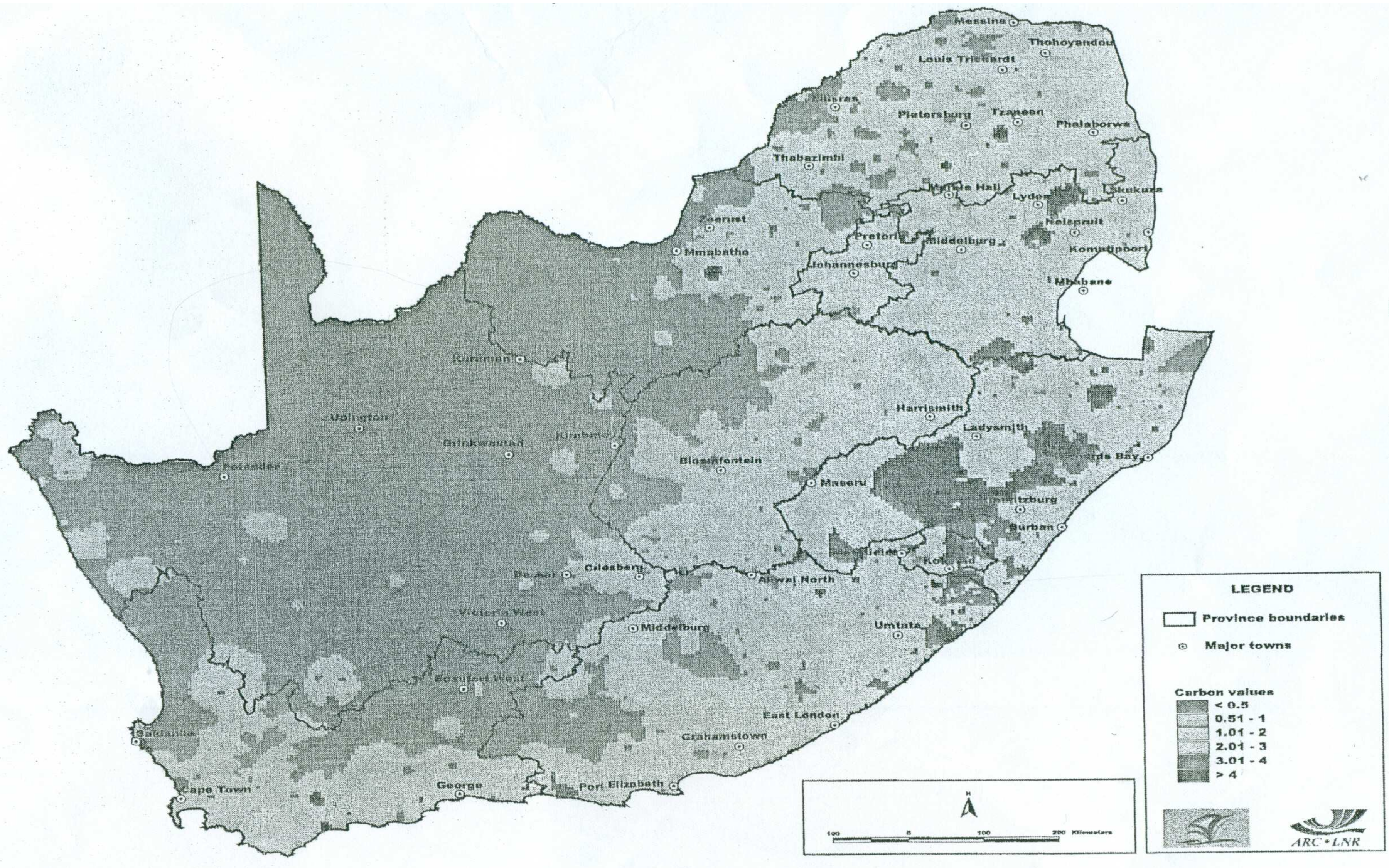


Figure 2.1 Organic carbon for virgin topsoils in South Africa (Barnard, 2000)

2.3 Relation of organic carbon stocks to soil forming factors

The relationship between the organic carbon content of soil and major soil forming factors is important in understanding the maximum equilibrium reached due to the interaction of these factors. The main important soil forming factors are time, climate, vegetation, topography, and parent material (Jenny, 1941). The level of equilibrium of soil organic carbon is influenced in order of importance by climate > vegetation > topography = parent material > time, with all soil forming factors being partly interactive (Stevenson & Cole, 1999).

2.3.1 Climate

Climate is the most important factor that determines the type of vegetation, the quantity as well as the rate at which it is decomposed thereby determining the levels of soil organic matter. The importance of climate as a soil forming factor is also verified by its clear and understood depth which it is included in Soil Taxonomy at high levels of classification (Soil Survey Staff, 1975). The key components of climate are moisture and temperature according to White (2006) who states that the effectiveness of moisture highly depends on

- The form and intensity of rainfall (precipitation)
- How it varies from one season to another
- Evaporation rate from the vegetation and soil
- The slope of the land
- The parent material permeability

As a measure of the effectiveness of moisture as a component of climate Thornthwaite (1948) developed the P-E index which can be referred to as the aridity index (Equation 2.1).

$$\text{Aridity index (AI)} = \frac{\text{Precipitation (P)}}{\text{Evaporation (E)}} \qquad (2.1)$$

However the interactions of the components of climate have been seen to affect several processes in different ways. Storage of C in biomass and soils is a function of climate, vegetation type, soil type, and land management (Birru, 2002; Mills & Fey, 2003a; Mills *et al.,* 2005a). Usually C storage is highly related to water availability which is a function of mean annual precipitation and temperature in both virgin and cultivated soils (Allison, 1973; Smith & Elliott, 1990; Jones *et al.,* 2004a; Mills *et al.,* 2005a). Generally climate, especially temperature and precipitation, are the most important factors for regulating soil organic matter (Alvarez & Lavado, 1998). Climate regulates the amount of vegetation cover, the quality and quantity of organic residues that are added to the soil as well as the rate of soil organic matter mineralization and decomposition and therefore soil organic matter turnover (Hontoria *et al.,* 1999).

There is a linear relationship between soil organic carbon and the mean annual precipitation. Hontoria *et al.* (1999) investigated the relationship between soil organic carbon and site properties such as climate and land use. Data for 766 soil profiles throughout peninsular Spain were used. The relationships between soil organic carbon and mean annual precipitation, mean annual temperature, land use, soil moisture regime, altitude, texture, and slope gradient were analysed. The results revealed that the variables best correlated with soil organic carbon are mean annual precipitation and the length of the dry summer season. Only 33% of the soil organic carbon variability was attributable to land use. Around 50% of the soil organic carbon variability was attributable to all the variables in the study. They concluded that if the relationships found between soil organic carbon and climate and land use would continue into the future, even a moderate change in climate of around 10% increase in temperature and 10% decrease in precipitation could actually lead to a 15% loss of soil organic carbon.

An expected relationship of increasing soil organic carbon with increasing water availability was not found by Mills *et al.* (2005a). They determined C storage in intact indigenous vegetation and under different land uses in South Africa. The sites were named after the vegetation in those areas. Soil carbon stocks were highest in the thicket at 168 t ha^{-1} and grassland at 164 t ha^{-1} (Table 2.1). Soil organic carbon of the thicket did not conform to the expected relationship, but they claim that “if thicket is excluded, then a relationship is apparent suggesting that factors such as geology, vegetation structure, rainfall distribution, and fire can override the effect of water availability”. There was an increase in carbon storage with an increase in the mean annual precipitation in the Karoo, xeric shrubland, and grassland sites. They concluded that the cooler, mesic climate of the grassland site contributed positively towards the maintenance of soil organic carbon stocks and offered a greater resistance to land use effects on organic carbon storage than in the semi arid sites.

Generally, low temperatures and high annual rainfall tend to affect the accumulation of soil organic matter positively whilst the degradation of C is favoured by low annual rainfall and high annual temperatures. This is because microbial activity is highest under moderate to low rainfall leading to more rapid humification of organic matter (Jones *et al.,* 2004a).

Table 2.1 Soil carbon stocks (0-500 mm) in untransformed indigenous vegetation (Mills *et al.,* 2005a)

Site	Mean annual precipitation (mm)	Geology	Soils	Carbon storage (t ha^{-1})
Thicket	250-400	Bokkeveld and Uitenhage sediments (shales, sandstones)	Loamy sands e.g. Oakleaf, Glenrosa	168
Xeric shrubland	350	Dwyka sediments (shale, tillite) Karoo dolerite	Sandy loams and clays e.g. Arcadia, Escourt	65
Karoo	250	Beaufort Group sediments, Karoo dolerite	Sandy loams e.g. Valsriver, Oakleaf	26
Grassland	900-1200	Karoo dolerite, Beaufort sediments (mudstones, sandtones)	Sandy clay loams e.g. Tukulu, Clovelly	164

2.3.2 Vegetation

Plant species have a significant effect on the organic matter content of soil. For example, other factors being constant, the carbon content of grassland soils (e.g. Mollisols) is substantially higher than that of forest soils (e.g. Alfisols) (Stevenson & Cole, 1999). This may probably be because of a higher biomass production and less microbial activity due to less aeration in grasslands. Dominy and Haynes (2002) also add that the establishment or maintenance of a permanent vegetation cover (e.g. pasture, thicket) will maintain or increase soil organic carbon.

Theron (1965) stated that the organic matter content of a soil is built up to a reasonably high level when kept under its natural grass cover. He added that it is stable at this level and is maintained there indefinitely as long as the vegetation is not overly disturbed. These theories stress the important relationship between soil organic matter and vegetation.

2.3.3 Topography

Topography influences the amount of organic matter in the soil by modifying the microclimate of the soil. Topography or relief includes knolls, slope and depressions. The tops and bottoms of slopes cause a gradient in temperature and moisture. This may be because lower areas tend to be cooler due to the denser cool air which flows to the lowest places in the landscape when compared to the warm air. However the soils that are formed in pans or depressions where the local climate is usually humid and cooler than in the hills have higher carbon contents than those in the hills where the local climate is dry and warm (Stevenson & Cole, 1999).

The changes in elevation normally affect the temperature, amount and form of precipitation as well as the intensity of the storms. All these factors interact to influence the type of vegetation found within an area. The slight changes in local climate and vegetation are related with slope and aspect of the valley. The steepness (angle) and the form (concave, convex and straight/smooth) of the slope is also very important (White, 2006).

However, soils found on the foot slopes have a higher C content. This may be because microbial activity depends highly on soil moisture. In the northern hemisphere, north facing slopes are normally wetter and the soil temperature cooler than the south facing slopes, therefore leading to a higher organic matter content for soils (McSweeney & Grunwald, 1998). In contrast, in South Africa the soils on the northern and western slopes are often warmer and drier than the soils on the southern and eastern slopes (Le Roux *et al.* 1999).

Topographic variability that has developed over pedogenic time scales, has the largest effect on the most stable pools of soil organic matter (Burke *et al.,* 1999). Topography actually involves the natural physical characteristics of a region which include slope percentage, slope aspect, slope type, terrain morphology, relief, and drainage. Several researchers have evaluated the influence of topography on soil organic carbon with different results.

Saby *et al.* (2008) reported on the spatial and temporal changes at the regional level in soil organic carbon in a mountainous French region using a soil-test database. A total of 23 329 soil organic carbon analyses were recorded between 1990 and 1994. The results showed a strong positive relationship between organic carbon and elevation. The effects of elevation are accredited to temperature and precipitation. Similarly, Jones *et al.* (2005) reported the highest soil organic carbon stocks at high altitudes in Europe. A similar relationship can be expected over parts of South Africa between the eastern and southern coastal belts and the Great Escarpment.

Lemenih & Itanna (2004) showed a relationship in soil organic carbon that is directly proportional to the mean annual precipitation and an inverse proportionality to mean annual temperature in a study case done on various vegetation types and arable lands along an elevation gradient in southern highlands of Ethiopia. The vegetation types were deforested and converted into arable lands along a 37 km elevation transect. The elevation transect covered five different eco-climatic zones that ranged from semi arid to cool sub-Afroalpine, each with a different vegetation type. Their results revealed that deforestation and subsequent cultivation caused a significant decline in soil C stocks but the losses varied between eco-climatic zones. They also concluded that deforestation and successive cultivation in the humid eco-climatic zone releases more carbon dioxide to the atmosphere. This was attributed to increased mineralisation when compared with the zones in the dry and low altitudes or cool and moist high altitudes which hinder organic matter decomposition by interfering with microbial activities. Most of the losses in soil occurred within the 0-10 cm depth. The losses ranged from 2-3% per year in the dry to humid forest and between 0.5-1% per year in the semi arid lowland and cool sub-Afroalpine eco-climatic zones. The results revealed a large difference of 191.7 Mg C ha^{-1} in soil C stocks along the elevation gradient and a wide range of differences in the rate and amount of soil organic carbon when natural vegetation were converted into arable lands.

2.3.4 Parent material

Jenny (1941) defines the parent material of the soil as the “initial state of the soil system” and not as the horizon of the lower strata which by chance may or may not be the parent material. The parent material of the soil influences its fertility, drainage and rate of weathering. The texture and adsorptive properties of the soil are highly influenced by the parent material thus affecting the carbon content of that soil. Good aeration and low moisture content found in sandy soils are the environmental conditions associated with low organic matter levels. On the other hand, clayey soils tend have a higher amount of organic matter because they are less aerated and have fine particle sizes (Stevenson & Cole, 1999). Organic matter also adheres to clay, preventing its mineralisation.

Light sandy textured soils are mostly dominated by low levels of organic matter (Scotney & Dijkhuis, 1990). Stevenson & Cole (1999) add that the quantity of C varies widely, from under 1% (by weight) in coarse textured soils (sands) to 3.5% in grassland soils (Mollisols) while poorly drained soils (fine textured) often have C contents of 10% or more (Table 2.2).

Table 2.2 Quantity of organic carbon in the soil (Stevenson & Cole, 1999)

Soil texture	Drainage	Organic carbon (%)
Coarse (sands)	Good	< 1 - 3.5
Fine (clayey)	Poor	≥ 10

Lobe *et al.* (2001) studied the effects of cropping on pools of C and N in coarse textured savanna soils of the South African Highveld. They discovered that the losses of soil organic matter occurred from all particle-size separates, although rate loss constants increased as particle size increased. The concentrations of soil organic matter actually decreased in the following manner: clay > silt > bulk soil > coarse sand > fine sand (Table 2.3). For example in Harrismith, after a period of 90 years of cultivation, organic carbon decreased from 52.9, 36.0, 20.6, 33.2, and 1.70 g kg^{-1} to 28.3, 13.2, 6.33, 3.99, 0.87 g kg^{-1} respectively. They discovered that even after the soil was cultivated for 100 years the properties of the soil continued to change, resulting in sustained loss of soil organic carbon.

The relationship between parent material and soil C was also shown in a study by Mills & Fey (2004a). The researchers examined the stocks of C to a depth of 500 mm in five contrasting biomes of South Africa which were exposed to different land use practices. The study sites were named after the vegetation types. They included: West Coast Renosterveld (Renosterveld), Central Nama Karoo (Karoo), Xeric Succulent Thicket (Thicket), Moist Upland Grassland (Grassland) and Mixed Lowveld Bushveld (Bushveld). Table 2.4 shows the biomes with their geology. Specifically, parent material had a significant effect on soil organic carbon. In grassland, soil organic carbon was higher in dolerite derived soils than sandstone derived soils with means of 164 and 97 t ha^{-1} respectively.

Table 2.3 Organic carbon concentrations in fine earth and particle-size fractions of the surface soils in three agro ecosystems (Lobe *et al.,* 2001)

		Organic C (g kg^{-1})				
Agroecosystem	Cultivation (years)	Clay	Silt	Bulk soil	Coarse sand	Fine sand
Harrismith	0	52.9	36.0	20.6	33.2	1.70
	90	28.3	13.2	6.33	3.99	0.87
Kroonstad	0	40.1	27.4	7.97	7.98	0.86
	90	16.3	14.7	2.68	2.19	0.61
Tweespruit	0	48.3	24.9	11.7	17.5	1.74
	90	20.7	10.4	4.32	3.93	0.45

Table 2.4 Geology at the study sites (Mills & Fey, 2004a)

Site	Geology
Renosterveld	Dwyka, Dolerite
Karoo	Dolerite, shale
Thicket	Shale, sandstone
Grassland	Shale, dolerite, sandstone
Bushveld	Granite, basalt

In follow up research Mills *et al.* (2005a) again proved that parent material highly influenced the amount of soil organic carbon in Xeric shrubland at the depth of 350 mm as shown in Table 2.1. Apparently, the dolerite-derived soils (Karoo) contained less soil organic carbon when compared with the Dwyka sediment-derived soils (Xeric shrubland) with 26 and 65 t ha^{-1} respectively. The effect of the soil type was also evident in the grassland where the sandstone-derived soils had ~40% less soil organic carbon than the dolerite-derived soils with 27 and 54 t ha^{-1} respectively (Mills *et al.,* 2005a).

2.3.5. Time

Time is a very important factor of soil formation that influences the amount of organic matter and its indices (C and N) in the soil. According to Stevenson & Cole (1999) "organic matter levels have been shown to increase rapidly during the first few years of soil formation, then the rate subsequently slows down and an equilibrium level characteristic to the environment under which the soil was formed is attained". They further state that time also contributes immensely to the transfer of organic matter into the lower horizons. This can continue for some time after equilibrium levels are reached in the surface layer. The total C quantity in the profile then stabilizes and remains essentially constant over time.

The interaction of moisture and time has a very high impact on the soil organic carbon levels. A longer period of time is actually needed for C levels to reach equilibrium in drier conditions than under wet conditions. The C content of the soil can fluctuate because of the variation of climate and the alteration of the soil composition due to processes such as leaching (removal conditions) and mineral deposition (cumulative conditions) (Stevenson & Cole, 1999).

The turnover time for global C is estimated between 30-40 years but is highly influenced by the particular ecosystem. Organic soils (Histosols) which are commonly found under waterlogged conditions have turnover times which exceed 2000 years while soils in the cold tundra regions have a turnover time exceeding 100 years. This may be caused by the different rates of decomposition which affect the accumulation of soil organic matter (McSweeney & Grunwald, 1998).

2.4 Effect of land use on soil organic matter

The relationship between land cover and soil organic matter storage is very important because it influences the loss of C to the atmosphere, or by erosion in which case C may be placed somewhere else in the landscape (Cai, 1996). The change from one land use practice to another could occur naturally or through human activity, such as for food or timber production. This change can be brought about by management practices that add little organic matter to the soil or increase the rates of organic matter decomposition, thus leading to reduced levels of organic matter in the soil. These land use practices include crop farming both dryland and under irrigation, stock farming and forestry.

2.4.1 Crop farming

Tillage is often highlighted as the main cause of soil organic matter decline (Allison, 1973; Prinsloo, 1988; Scotney & Dijkhuis, 1990; Tate, 1992b; Du Toit *et al.,* 1994; Du Preez & Wiltshire, 1997; Stevenson & Cole, 1999; Lobe *et al.,* 2001; Mills *et al.,* 2003a; Jones *et al.,* 2004a; Yadav & Malanson, 2007). Cultivation of virgin soils results in a decrease in soil organic carbon and total nitrogen contents (Van Zyl & Du Preez, 1997; Helfrich *et al.,* 2006). This decline of organic carbon content in soils brought under cultivation is mainly attributed to reduction of input of organic materials to soils, acceleration of the decomposition of soil organic matter and promotion of soil erosion (Prinsloo, 1988; Cai, 1996). New lower levels of organic matter are accomplished under the cultivation of natural or semi-natural inhabitants. These levels may be 30 to 60% lower in cultivated soils compared to their undisturbed (or virgin) equivalents (Rusco *et al.,* 2001).

2.4.1.1 Cultivation under dryland

Theron (1949) found that it was quite impossible to maintain the organic matter content of the soil, especially under normal dryland cultivation, by additions of manure or compost or the practice of green manuring. He goes on to say that, we have to content ourselves with a loss of 30 to 40% of organic matter in the virgin soil after some 15 years of cultivation. From the studies of Theron (1949) and later Lobe *et al.* (2001) it is clear that the rate of loss of soil organic matter, under cultivation, decreases rapidly over the years. Jenny (1941) also states that the reduction in soil organic matter is usually exponential, declining rapidly during the first 10-20 years, and then continues more slowly until a new equilibrium is reached after 50-60 years. Allison (1973) goes on to say that when a virgin soil is cultivated, the organic matter content usually decreases to perhaps 50-60% of its climax level within a period of 25 years and the oxidation is likely to continue at a decreasing rate for many additional years.

Prinsloo *et al.* (1990) investigated the effect of present or past cultivation on nitrogen fertility in some central Free State soils with organic carbon being one of the measured parameters. This was done by comparing paired samples of cultivated or reverted soils with uncultivated soils. Large losses of organic carbon from the surface layer (0-0.15 m) were recorded with the smallest being 8%. The organic carbon content in the 1 m depth had declined by an average of 36%. Cultivation therefore increased the mineralization of soil organic carbon.

The effect of cultivation on the organic matter content of selected soils was examined by Du Toit *et al.* (1994) in the central parts of South Africa. Virgin soils served as a reference. The virgin and cultivated topsoils were sampled to a depth of 0-200 mm at 50 sites. They found that 5-90 years of land use for cropping of soils resulted in a loss of 10-75% of organic carbon and 5-73% in the case of total nitrogen. They also discovered that the losses of organic carbon were consistently larger than total nitrogen resulting in slightly lower C:N ratios than virgin soils.

A general depletion pattern for organic matter due to cultivation was found for the area under study by correlating the cultivation index of each of the 50 sites with its relevant cultivation period. The correlation coefficient (R) of 0.52 was recorded. Three distinct patterns were revealed. There was a sudden loss of organic matter during phase one, which was the first five years of cultivation. The rate decreased during phase two until an equilibrium was reached after about 35 years of cultivation. There was little or no additional decrease in organic matter content during the third phase (Du Toit *et al.,* 1994).

The decomposition rate of organic matter was higher in the ecotopes from the warm drier areas than in the ecotopes from the cooler wetter areas, but the percentage organic matter lost was actually greater in the cooler wetter areas. A new organic matter equilibrium was reached faster in the warm drier ecotopes (after 5-10 years) than in the cooler wetter ecotopes (after 40-60 years). In the virgin soils, the organic carbon content increased with increasing aridity indices and increasing fine silt-plus-clay contents (Table 2.5; Du Toit *et al.,* 1994).

Table 2.5 Organic carbon from five ecotopes in the central parts of South Africa (Du Toit *et al.,* 1994)

Ecotope	Aridity index	Fine-silt-clay (g kg^{-1})	Organic C (g kg^{-1})
1	0.20	100	3.83
2	0.24	137	6.25
3	0.29	605	16.68
4	0.33	235	10.77
5	0.36	270	19.20

Lobe *et al.* (2001) studied the effect of cropping period on C and N in coarse-textured savanna soils of the South African Highveld. The cropping period varied from 0-98 years in three agroecosystems in the Free State province. Soil organic C and N was reduced by 65 and 55% respectively, due to long term cultivation of native grassland. Organic carbon losses were recorded from all particle size fractions. However, organic carbon decreased with particle size which shows that organic matter associated with clay is more resistant to mineralization than in sand fractions.

Some developments have been made in the sugar industry on the effect of cultivation on soil organic matter more especially in the KwaZulu-Natal region. Qongqo & Van Antwerpen (2000) took samples from cultivated and virgin soils from two different climatic regions in KwaZulu-Natal. The soils were analysed to identify changes in selected soil chemical and physical properties resulting from continuous sugarcane production. The results revealed that as the period of cultivation increased there was a decrease in organic matter with a corresponding increase in bulk density. There was a significant loss of organic matter in the South Coast region (from 4.7% to a mean value of 2.4% at a rate loss equivalent to 0.04% per year) due to cultivation but not in the Midlands (from 6.06% to 5.7% at a rate of 0.01% per year; Figure 2.3).

The loss of soil organic matter and associated soil properties under long-term sugarcane production on two contrasting soils was studied by Dominy *et al.* (2002). The investigations were done in the 0-100 mm layer of a sandy Glenrosa soil and a red Hutton soil from the sugar belt in the KwaZulu-Natal province in South Africa. They reported that the organic carbon content at both sites under undisturbed vegetation was between 40 and 50 g C kg^{-1} and that it decreased exponentially with increasing years under sugarcane production. After 20-30 years under sugarcane, organic carbon content had declined to about 33 g kg^{-1} for the Hutton and 17 g kg^{-1} for the Glenrosa soil. They concluded that the higher organic matter content sustained at the Hutton site was accredited mainly to clay protection of organic matter since the clay content of the Hutton soil was 62% in contrast to 18% for the Glenrosa soil.

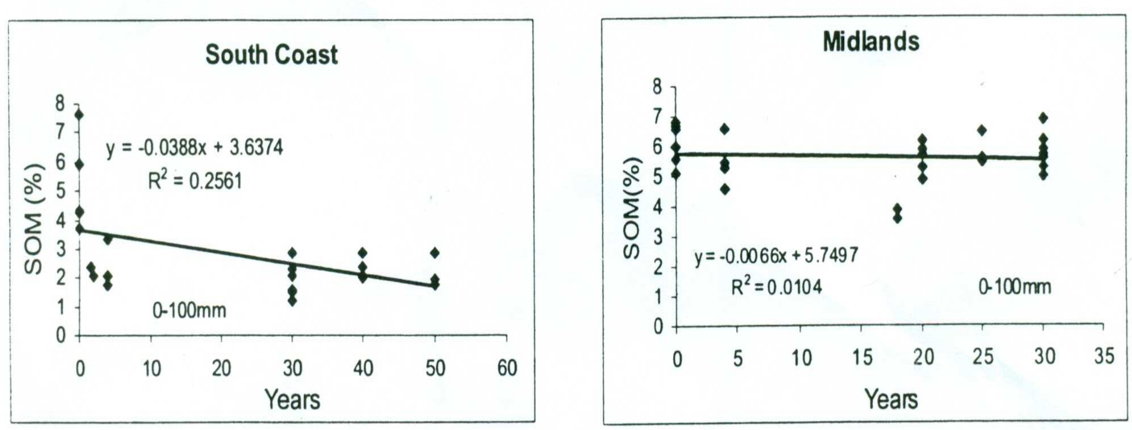


Figure 2.3 Soil organic matter changes with an increase of the period under cultivation for two regions (Qongqo & Van Antwerpen, 2000)

2.4.1.2 Cultivation under irrigation

When soils are irrigated, a more favourable water regime is created for the mineralisation of organic matter throughout the year. More frequent tillage and heavier fertilization is needed for intensive cropping on irrigated soils than on cropped dryland soils. This can result in either acceleration of organic matter decomposition or greater accumulation of soil organic matter due to higher biomass production (Du Preez & Wiltshire, 1997).

Van Antwerpen & Meyer (1996) quantified the organic matter content of soils under sugarcane production in northern KwaZulu-Natal. Soil samples from 29 virgin and adjoining cultivated fields with 15 originating from dryland and 14 from irrigated areas were analysed. The soil forms from these areas included: Westleigh, Fernwood, Inanda, Willowbrook, Mispah, Milkwood, Glenrosa, Nomanci, Katspruit, Kroonstad, Swartland, Bonheim, Hutton, Shortlands, Mayo, and Oakleaf. The results (Table 2.6) showed that cultivation reduced organic matter significantly in both areas, but the decrease was lower as the depth increased. Irrigated areas lost more organic matter than the dryland areas.

Table 2.6 Changes in organic matter between paired sites in a dryland and irrigated area (Van Antwerpen & Meyer, 1996)

	Organic matter (%)					
Depth (mm) virgin	Dryland			Irrigated		
	Mean cultivated	Mean difference	Mean virgin	Mean cultivated	Mean difference	Mean virgin
150	3.87	3.31	0.56*	2.40	1.88	0.52*
300	3.33	3.19	0.14	2.08	1.69	0.38*
450	3.16	3.04	0.12	1.46	1.39	0.08

*Significant at P=0.05

The changes in the organic matter and nutrient contents of some South African irrigated soils were investigated by Du Preez and Wiltshire (1997). The samples were collected from virgin and cultivated topsoils of the soil forms: Plooysburg, Kimberley, Augrabies, Addo, Hutton, and Clovelly. The vegetation mostly included grassland, shrubs, and trees and the years of cultivation ranged from 1 to 50 years in three irrigation schemes (Ramah, Riet River, and Vaalharts). The virgin topsoils (<200 mm depth) from all irrigation schemes had low organic matter contents, with organic carbon means of 4412 ± 185 mg kg^{-1} from Riet River, 3872 ± 322 mg kg^{-1} from Ramah and 4819 ± 318 mg kg^{-1} from Vaalharts. There was a linear increase in soil organic matter content with mean annual rainfall in the three irrigation schemes (organic C = 6.32rainfall + 2034; R^2 = 0.99). They attributed the variation of soil organic matter to the differences in botanical composition, basal ground cover, and biomass production which were unfortunately not documented. They discovered that irrigation, with the associated increase in biomass production, to some extent offset the effect of cultivation in causing a decline in soil organic matter. They concluded that irrigation and fertilization are likely to increase mineralization of soil organic matter.

2.4.1.3 Crop residue retention

Cultivation under dryland and irrigation result mostly in losses of soil organic matter if precautionary measures are not taken. Thus worldwide there is an inclination towards retaining crop residues on or near the soil surface (Graham *et al.,* 2002) which is commonly referred to as conservation tillage. In this approach, regular burning or deep incorporation of crop residues are therefore not practised since both lead to a decrease in soil organic matter (Jones *et al.,* 1990). Plant residues are a good source of soil organic matter therefore conservation tillage has a great effect on the total soil organic matter.

Van der Watt (1987) investigated the effect of reduced tillage on soil organic carbon from four localities in the Free State and Transvaal. The soil forms included the Avalon, Glencoe, and Hutton. He compared the organic carbon contents of the 0-150 mm and 150-300 mm layers of conventionally tilled, stubble-mulched and no-tilled soils. An increase of 38% in organic carbon content of the top layer was found in the stubble-mulch tillage when compared with conventional tillage.

Little of South Africa’s maize crop is directly drilled without residue burning or removal but the farmer’s curiosity in this matter is rising as it may play a significant role in conservation farming. Mallet *et al.* (1987) found after 8 years of direct-drill maize production at Cedara on a Hutton/Doveton clay loam, organic carbon levels in the top 20 mm were higher than in conventionally tilled plots and the top 120 mm had become denser. After another 4 years they discovered that the surface organic carbon levels had increased from 3.8 to 4.7% in the direct-drill plots but had remained unchanged in the conventionally tilled plots at around 3.3% while the soil dry bulk densities stabilized. The organic carbon content of the top 25 mm of the ploughed plots remained nearly constant after 4 years while the organic carbon content of the direct-drill plots had risen to 4.74%. Therefore they agreed that this method can be used as a way of conserving soil and water thus decreasing the loss of soil nutrients and organic carbon but the subject of whether it can be applied to all regions remains to be explored.

The influence of different wheat residue management practices, that were continued for about 20 years, on organic matter content was studied on an Avalon soil in a long term trial in Bethlehem in the Eastern Free State in South Africa. The applied treatments included two methods of straw disposal (burned and unburned), three methods of tillage (stubble mulch, ploughing, and no tillage) and two methods of weed control (chemical and mechanical). Samples were taken at various depth intervals and organic matter indicators (organic C and total N) were measured. The results showed that the effect of either straw burning or weeding method on organic matter on an Avalon soil was small compared to that of tillage practices especially on the upper 100 mm soil. A higher organic carbon content was found in the unburned than burned plots to a depth of 450 mm. There were no significant interactions between the treatments on either organic C or total N, but based on these two indices to approximately 150 mm depth, ploughing combined with mechanical weeding resulted in the lowest organic matter content, whereas no tillage combined with chemical weeding resulted in the highest organic matter content. The latter combination was recommended in order to retain and even increase the organic matter content of this Avalon soil, especially in annual wheat cropping (Kotzé, 2004; Kotzé & Du Preez, 2007).

The supply of large quantities of organic matter within the South African sugar industry is limited and growers have to make use of what is available (Van Antwerpen *et al.,* 2002). However, the most practical way of maintaining or improving soil fertility under cane production is green cane harvesting with trash retention (Graham *et al.,* 1999; Van Antwerpen *et al.,* 2002).

The practice of burning cane before harvest under the monocultural system of sugarcane production in South Africa is the major reason for the loss in organic matter from sugarcane soils (Van Antwerpen & Meyer, 1996) which leads to increased soil degradation. However, Van Antwerpen *et al.* (2002) discovered that trashing has the potential of conserving soil organic C even though this can vary depending on the variability of rainfall. Their results showed that trashing under irrigation is capable of maintaining the active fraction of organic matter in the topsoil, which is not possible under conventional burning practices. They recommended that trash can be used as a free source of organic matter that is available to all growers and has been proven to be beneficial in sugar cane production.

After 59 years of burning and green cane harvesting with or without annual fertilizer applications carbon levels were investigated in a Vertisol at Mount Edgecombe, South Africa. Graham *et al.* (2002) found that concentrations of organic carbon in the surface 100 mm of the soil increased with fertilizer applications and with increasing amounts of crop residue returned. The highest amount of organic carbon was found where crop residues were either burnt prior to harvest with the harvest residues raked off, than where they were burnt prior to harvest with the harvest residues left on the soil surface and lastly where they were left unburnt with all the trash left on the soil surface. Among their conclusions they discovered that trash retention and annual fertilizer applications have substantial long-term effects on organic matter status as well as other chemical and physical soil properties. This latest study correlates with the one done earlier on sugarcane production by Graham *et al.* (1999) where they concluded that, where green cane harvesting with retention of a trash blanket is practiced, there can be an increase in soil organic matter. In both studies they discovered that fertilised treatments tended to have a higher organic matter and microbial biomass C content than unfertilised treatments, reflecting higher yields and organic matter returns under fertilisation.

The sustainability of agricultural systems is greatly dependent on optimizing the balance between inputs and outputs of nutrients (Belay *et al.*, 2002). This can be done by making sure that the nutrients that were removed from the soil are returned by promoting practices such as legume based crop rotation or by application of organic and inorganic fertilizers. In on-going research at the University of Pretoria, South Africa, Belay *et al.* (2002) compared the residual effects of manure and NPK fertilizers on selected soil nutrients that included organic carbon. They discovered that organic carbon increased due to the residual effects of manuring alone or in combination with NPK plots. They also found that the carbon input in organic fertilizers was about 47% higher than in manured plots. There was greater increase in microbial activity in the NPK treatment probably due to the high decomposability of organic matter. They concluded that management systems can determine the amount of C added to the soil as well as the decomposability of soil organic matter.

Entry *et al.* (2002) examined whether land management change for cropping under irrigation from mouldboard ploughing to conservation tillage or pasture could sequester additional C. They concluded that around 2.6 x 10^8 ha of land worldwide is presently irrigated. Therefore if this area was to be expanded with 10% and the same amount of land was to be transformed back to native grassland then about 5.9% of the total C released in the next 30 years could be potentially sequestered. They concluded that irrigation could bring positive results on reducing CO_2 atmospheric concentrations by increasing biomass production therefore contributing to the addition of carbon to the soil.

2.4.1.4 Perennial pasture establishment

A grass ley is sometimes used to restore soil organic matter losses from cultivated land. In other instances pastures of a more permanent nature are used for this purpose. The effects of both approaches are dealt with here.

Theron (1961) studied the influence of the ley grass *Eragrostis curvula* on the rehabilitation of humus. This was done in a soil that had been previously cultivated for around 30 years but was already showing signs of rehabilitation. Surprisingly he discovered that the rehabilitation of humus was very small and concluded that in order to obtain an effective build-up a period of 8 years was needed.

When agricultural land is no longer used for cultivation and is allowed to revert to natural vegetation or replanted to perennial vegetation, soil organic carbon can accumulate. This accumulation process essentially reverses some of the effects responsible for soil organic carbon losses from when the land was converted from perennial vegetation (Post & Kwon, 2000). When a perennial grass is established on a soil that has previously been cultivated, the mineralization of organic matter which took place freely under the annual crops, is inhibited as soon as the grass roots occupy the soil. Therefore, this leads to a build up of soil organic matter. In order to maintain fertility, in the absence of suitable legumes, heavily fertilized leys of at least three years can be of great importance (Theron & Haylett, 1953).

When a cultivated soil has been transformed to pasture, there is an increase in nitrogen as well as organic carbon content which is known as secondary succession (Prinsloo *et al.,* 1990). This may be caused by a decrease in aeration in pastures which decreases the rate of organic carbon loss as well as a decrease in the erodibility of the tilled layer. The effect of erosion in the absence of cultivation and enhanced vegetation cover is rather easily explained, because the exponential decrease in soil organic matter concentration with depth means that relatively little topsoil need be lost to reduce significantly the total soil organic matter content (Mills & Fey, 2003a). West & Post (2002) state that loss of soil organic carbon can be reversed by ceasing cultivation and returning to the original land cover or other perennial vegetation, especially grasslands.

Birru (2002) investigated the restoration of organic matter when cultivated land is converted to perennial pasture in three agro-ecosystems (Harrismith, Kroonstad, and Tweespruit) in the Free State. The lands in the agroecosystems were continuously cultivated for more than 20 years and had been converted to perennial pastures of different ages. Organic matter was evaluated at three depths: 0-50 mm, 50-100 mm, and 100-200 mm. His study proved that rate of organic matter restoration in cultivated land reverted to perennial pasture depends highly on the prevailing climate, topography, soil, and management practices even though the change was very slow. Only 25% of the organic carbon, which had been lost during 20 or more years of cultivation, had been restored after approximately 15 years under perennial pasture. The organic carbon content decreased with depth, the highest being in the 0-50 mm layer. Natural resource factors and management techniques caused a wide difference in the rate of organic matter restoration between the sites. The techniques that contributed positively included: a favourable water regime, adequate rooting depth (500 mm), clay content above 12%, gentle slopes, an aridity index above 0.35, and the presence of a legume in the pasture.

2.4.2 Stock farming

Bühmann *et al.* (2006) did a study on the plant nutrient status of soils of the Lusikisiki area in the Eastern Cape, South Africa. The soil forms included: Cartref, Shortlands, Mayo, Inhoek, Glenrosa, Kranskop, Magwa, Mispah, Swartland, Bonheim, Vilafontes, and Inanda. A total of 61 samples were taken from 15 profiles at depths of 0-150 mm, 150-300 mm and beyond 300 mm.

The organic carbon content of the surface layer ranged from 1.57% to 5.52%. Soils with humic A horizons had an organic carbon content ranging from 3.25% to 5.30% and an average value of 3.64% which was higher than the overall average of 3.22%. Land use was not considered to be the determining factor for this variability because all profiles were in natural grassland. The results showed that the organic carbon content was not related to parent material in the Shortlands and Bonheim soil forms which are dolerite-derived soils. However, the extensively diverse degrees of soil development in the Mispah and Inanda soil forms resulted in approximately equal values of organic carbon. There was also a stronger correlation between cation exchange capacity (CEC) and base status in the A horizon with organic carbon content (r = 0.97) than with the clay content and/or nature of clay fraction (r = 0.17). The CEC of the soils from the Lusikisiki district ranged from 3.1 cmol kg^{-1} to 30.07 cmol kg^{-1} and the sum of the base cations in the A horizons varied between 0.87 and 18.36. The organic carbon content is actually high for South African conditions, averaging 3.64% in the A horizons. This high organic carbon - related CEC is reflected in a close association between exchangeable plant nutrients and organic carbon. They concluded that organic carbon makes an important contribution to the amounts of nutrients the soils can store and is of critical importance to their fertility (Bühmann *et al.,* 2006).

Fire is used as a vital practice for the management of grazed savanna grasslands in the Eastern Cape, South Africa (Materechera *et al.,* 1998). The effect of veld burning on soil properties such as organic matter in plots of a 17 year old experiment with different burning frequencies was investigated on a Glenrosa soil. The results revealed that burning reduced the organic carbon content of the soils significantly especially in the plots where the veld was burnt every year (Table 2.7). The high organic carbon content in the unburnt plots would be due to the enhanced biomass addition and possible higher microbial activity in the rhizosphere of the grass. Therefore they recommended that other methods be used to sustain soil fertility rather than burning.

The results of Materechera *et al.* (1998) actually correlate with what was found by Jones *et al.* (1990) in the Kruger National Park. Part of their study was to determine which soil organic factors were responsive to the burning regime. They discovered that the organic carbon content in the 0-150 mm layer was 25% higher in the protected plots than in the burned plots after 34 years. There was a gradual decrease in C as the fire frequency increased. This decrease in C in the soil was due to combustion.

Table 2.7 Organic carbon content in soils of different burning regimes (Materechera *et al.,* 1998)

Burning frequency	Burn frequency (year)	Organic carbon (%)
Complete protection	0	1.23
Annual burning	1	0.71
Triennial burning	3	0.83
Sexennial burning	6	0.77

The effects of burning native grassland on soil organic matter were explored by Fynn *et al.* (2003). This was done on50 year data where different times and frequencies of burning had been compared. They discovered that there were significant decreases in organic carbon in the 0-20 mm layer due to annual and biennial winter burning and biennial and triennial autumn burning. Surprisingly, burning in spring did not cause a significant difference in organic carbon probably because considerable amounts of litter were either decomposed or were incorporated into the soil by faunal activity before burning. Burning also caused a decrease in light fraction and hot water-extractable C in the 0-20 mm layer. An increase in these parameters, and in microbial biomass C and root density in the 0-40 mm layer, was also recorded.

Mills & Fey (2004b) examined whether frequent burning increased the tendency of the soil to crust and altered its chemistry. They studied the topsoils from 19 sites in Mpumalanga, KwaZulu-Natal and the Eastern Cape where annual burning and fire exclusion experiments had been conducted for at least 28 years. Their results revealed that the total C and labile C in the soil from 0-10 mm were significantly lower in burnt plots than unburnt plots (with means of 0.8% vs. 2.7% for burnt and unburned plots respectively). Because one of the most important functions of soil organic matter is to promote soil aggregation, a decrease in soil organic matter due to burning led to a decline in aggregate stability.

The effect of land use on soil organic matter and crusting was reviewed by Mills & Fey (2004c). Their review showed that land use in South Africa causes a distinct reduction in soil organic matter content. Practices such as removal of vegetation cover either by ploughing, grazing or burning reduce soil organic matter by reducing its inputs and improving microbial activity. Soil organic matter inputs are reduced by burning because of the combustion of above-ground biomass and leaf litter, especially in savannas and grasslands.

The conservation of vegetation cover would certainly seem to be a basic requirement for maintaining soil quality in rangelands. Du Preez & Snyman (1993) discovered that there is a relationship between veld condition and soil organic matter. Three veld conditions (poor, moderate and good) were established in an experiment in a *Themeda-Cymbopogon* grassland of the Free State in Bloemfontein on a Bloemdal soil. Basal cover decreased linearly with veld condition. After 15 years, the poor and moderate veld had 25% and 16% less organic matter respectively, than the good veld. A loss of 33% organic carbon in the upper 50 mm was incurred where a veld of good condition was converted to a poor veld condition. They concluded that this might have been caused by lower biomass production and greater soil temperatures in the poor and moderate veld compared to the good veld and this resulted in less organic matter being returned to the soil.

In subsequent research on a similar soil, Snyman & Du Preez (2005) determined the impact of rangeland degradation on soil characteristics including soil organic matter and its impact on soil quality. Sampling was from rangeland artificially maintained in three different rangeland conditions, *viz.* good, moderate and poor. Organic matter content decreased with rangeland degradation owing to the lower basal cover of a poor rangeland. They discovered that after only 5 years following degradation, organic carbon was significantly lower (22.15%) over the first 50 mm soil layer in poor condition than that of good condition rangeland. They also found that rangeland degradation lengthened the replacement of the root system by about a year and decomposition time of litter by 8 months. Since the roots are the major C sources in the soil, the poor root mass with rangeland degradation contributed immensely to the slow build up of soil organic matter.

Mills *et al.* (2005b) investigated the effects of goat pasturalism on ecosystem C storage in semi arid thicket in the Eastern Cape, South Africa. The study was from a dense vegetation of tall shrubs to an open landscape dominated by short-term grasses and forbs. They discovered that C storage in intact thicket was surprisingly high for a semi arid region, with an average of 76 t C ha^{-1} in living biomass and surface litter and 133 t C ha^{-1} in soils to a depth of 300 mm. The dominance of *Portulacaria afra* (*P. Afra*) probably led to the exceptional C accumulation in the thicket. The transformed thicket has approximately 35% less soil C to a depth of 100 mm and approximately 75% less biomass C than intact thicket. Therefore, they concluded that restoration of transformed thicket landscapes could consequently recoup more than 80 t C ha^{-1}.

As a means of rehabilitation of degraded areas as well as conservation of organic carbon on previously cultivated lands, Hansen-Quartey *et al.* (1998) suggested the planting of *Artemisia afra* (*A. Afra*). Even though *A. Afra* did not cause any significant difference in organic carbon in the upper 100 mm but increased the aggregate stability. The organic carbon under *A. Afra* was 1.06% whilst the control had 0.91%. They recommended that it should be introduced on cultivated agricultural lands as this will lead to a reduction in soil erodibility and could be economically beneficial and improve soil management.

A study was done by Mills & Fey (2004a) on soil C and N in five contrasting biomes of South Africa exposed to different land uses. The study sites were in different parts on South Africa with different soil forms, and named after the characteristic vegetation types namely: West Coast Renosterveld (renosterveld), Central Nama Karoo (Karoo), Xeric Succulent Thicket (thicket - goat transformed, pseudosavanna), Moist Upland Grassland (Grassland) and Mixed Lowveld Bushveld (Bushveld). They found that the stocks of soil C varied between regions in the following order: Thicket > Grassland > Renosterveld > Bushveld > Karoo. In the 0-500 mm layer of soil, stocks of C in virgin veld ranged from 21 t ha^{-1} in Karoo to 168 t ha^{-1} in Thicket. The mean soil C of 5.6% in the 0-100 mm in the thicket was approximately five times greater than expected in the semi-arid region. They also discovered that land under cultivation with wheat or maize, farmed intensively with goats and burnt frequently, tended to have lower C and N than virgin veld. Stocks of soil C and N were greater under woody vegetation cover than in open exposed soils.

Grazing lands may have a high potential to sequester C if good management practices which add organic matter and reduce soil erosion are followed. Shresta & Stahl (2008) examined the soil organic carbon and soil microbial biomass carbon contents inside and outside grazing exclosures. The four exclosures were established more than four decades ago in the semi-arid sagebrush steppe of Wyoming in the United States of America. Comparison between the non-grazed and grazed exclosures was done to examine the effects of long term grazing on soil organic carbon accumulation. Soil organic carbon in these soils ranged from 3.67 to 53.8 mg g^{-1} dry soil. They discovered that there was no significant difference in soil organic carbon between grazed soil and soil not grazed for more than 40 years. The difference was not significant due to treatment (grazing exclusion) in three of the four sites. However the loss of soil organic carbon was reduced probably by the low stocking rates in the sites. At two sites, microbial biomass carbon was more in the ungrazed soil than in the grazed soil. The reason may be because long term grazing encourages the improvement of the labile soil C pool.

Mestdagh *et al.* (2009) investigated the changes in soil organic carbon stock in Flemish grassland soils. This study was done from 1990 to 2000. Their results showed that the soil organic carbon stock was estimated at 38 Mt soil organic carbon in 1990 and 34 Mt soil organic carbon in 2000 in the grassland soils. The decrease in soil organic carbon stock was mostly explained by a decline in the organic carbon content (accountable for 71% of the decrease) and also by a decrease in the grassland area (accountable for 29% of the decrease). The decrease in the grassland area was due to an increase of 37% in maize production during the period of 1990 to 2000. There was also a 9.2% decrease in livestock numbers during that period. They discovered that in order for grasslands to become sinks instead of sources of carbon dioxide the lost grassland areas have to be recovered and management practices which build up soil organic carbon have to be put in place.

2.4.3 Forestry

Carbon stored in forest ecosystems represents a substantial part of the global C stock and world wide forests contain ~70% of all plant C and ~20% of all soil C. The sequestration of carbon can be attained after the conversion of intensely agricultural cropping to extensive land use practices such as afforestation and natural succession ecosystems (Degryze *et al.,* 2004).

Three tree species were selected for a study in the Weatherley catchment in South Africa from 2002. The trees: *Pinus patula, Pinus elliottii* and *Eucalyptus nitens* received specific areas of the catchment to cater for their different soil requirements. The soils in this area ranged from very poorly drained hydromorphic (Katspruit form), to excessively drained without hydromorphy (Hutton and Oakleaf forms). Organic carbon content decreased linearly from an average of 1.7 Mg m^{-3} x 10^{-2} in the top 50 mm layer to 0.5 Mg m^{-3} x 10^{-2} in the 600-700 mm. Organic carbon decreased by approximately 0.17 Mg m^{-3} x 10^{-2} per 100 mm layer irrespective of the nature of the B horizon (Le Roux *et al*., 2005).

The accumulation of organic matter is likely to be maximum in the topsoil under grassland but a noticeably different accumulation can be expected under afforestation. This is because of the deep penetration of the tree roots which leads to more organic matter in the subsoil layers. The total organic carbon content of the 27 profiles representing all the soils in the catchment is given in Table 2.8. They also concluded that there is a considerable variation in organic carbon content between the same kinds of soils in the different tree species. The highest variation was found in the very poorly drained soils. The total organic carbon in the 0-1200 mm varied from 75 Mg ha^{-1} in the control sites, to 82 Mg ha^{-1} in the *P. patula* area to 112 Mg ha^{-1} in the *P. elliottii* area. However, when the control sites are excluded the variation in organic carbon content was relatively small (Le Roux *et al*., 2005).

Table 2.8 Total organic carbon content of the soils in the Weatherley catchment (Le Roux *et al*., 2005).

Soil group	Organic C (Mg ha^{-1})
Excessively drained soils (Hutton and Clovelly forms)	111.1
Moderately well drained soils (Bloemdal and Pinedine forms)	85.1
Very poorly drained soils (Katspruit, Longlands, Kroonstad, Westleigh and Klapmuts form)	97.0
Freely drained soils (Tukulu forms)	88.3

Afforestation and deforestation both play an important role in the soil organic matter contents. Most of the loss in soil organic matter occurs within 10 years of clearing of forests or native grassland, with the size of loss depending on the type of soil (Gregorich *et al.,* 2007). As a recommendation, Prinsloo *et al.* (1990) found that the reversion to pasture from cultivation appeared to restore fertility where leguminous trees were present, but not in their absence which emphasizes the importance of trees in soil organic matter restoration.

2.5 Carbon sequestration

Increasing the amount of C in the soil can help reduce the concentration of carbon in the atmosphere. Moreover, soils can be used as carbon sinks especially under the Kyoto Protocol where soil organic carbon is very important in the global carbon sink. Inevitably, the changes in land use practices cause a great impact in the amount of C stored in the soil by changing the amount of C added as well as depleted in the soil. The most common practices that cause an addition of carbon dioxide to the atmosphere are fossil fuel combustion, as well as changes in land use practices such as clearing of forests and cultivation. Mills *et al.* (2003b) state that the practices have so far resulted in a 38% increase in atmospheric carbon dioxide since pre-industrial times. Stevenson & Cole (1999) add that deforestation also contributes to C losses to the atmosphere.

The efficiency of C sequestration by the grassland vegetation in the Weatherley catchment was explored and compared with predicted aforestration values. The C sequestered in the grassland was estimated to be 1700 kg C ha^{-1} yr^{-1}. The mean annual ET_{grass} was estimated to be 824 mm.

Therefore the C sequestration efficiency by the grassland was 1700/824 = 2.06 kg C ha^{-1} yr^{-1} mm^{-1} . The C sequestration efficiency of the area afforested with *P. Patula* (*P. elliottii* is expected to be the same) was estimated to be 2.75 kg C ha^{-1} yr^{-1} mm^{-1}. However in a period of over a 20 year growing cycle the trees will be expected to have sequestered around 58.5 Mg C ha^{-1} and the veld grass around 33.9 Mg C ha^{-1} above ground (Le Roux *et al.,* 2005).

Mills *et al.* (2003b) state that sequestered C is presently being traded on the international market for US$8 per ton. They further add that if the Kyoto Protocol comes into effect, soils and vegetation are likely to be accepted as C sinks to offset C emissions. The Protocol requires developed countries to reduce their green house gas emissions (GHG) below levels specified for each of them in the treaty. These targets must be met within a five-year time frame between 2008 and 2012, and add up to a total cut in green house gas emissions of at least 5% against the baseline of 1990 (UNFCCC, 2008). The green house gases of primary concern are carbon dioxide, methane, and nitrous oxide. An international market for C has thus been developed whereby C emitters are paying for the establishment of C sinks.

An exploration on whether a market for carbon is likely to provide incentives for South African farmers was done in West Coast Renosterveld (Renosterveld), Central Nama Karoo (Karoo), Xeric Succulent Thicket (Thicket) and Moist Upland Grassland (Grassland). The farmers in those areas changed their present land use practices and started to farm for C credits. The carbon stocks of above and below ground biomass were calculated in the four vegetation types. According to the results the intact thicket and kikuyu grass pastures planted in grassland have higher C stocks than in the Renosterveld and Karoo sites (Table 2.9). The results also showed that soil C dominates the carbon stocks in all vegetation types. Carbon storage within intact subtropical thicket can go beyond 200 t C ha^{-1} (Mills *et al.,* 2003b; 2005a). Therefore this may bring positive results to farmers involved with C sequestration only if soil C is increased. Recommendations suggested that research into the potential rate of C sequestration in South African landscapes should be undertaken for the development of the estimation of potential benefits to farmers and to secure a share in the international carbon trade (Mills *et al.,* 2003b).

The potential rate of C sequestration as a prerequisite for determining the potential returns from carbon credits in two thicket restoration sites in the Eastern Cape, South Africa was assessed by Mills & Cowling (2006). The *P. afra* (*Portulacaria afra)* in the Krompoort and the Kudu Reserve were planted from 1976 until 1998 and 1983 respectively. They concluded that ecosystem C storage in intact thicket in the Eastern Cape exceeded 20 kg m^{-2}, which is an unusually large amount for a semiarid ecosystem. However, intense browsing caused by goats has actually transformed the thicket into an open savanna which resulted in C losses greater than 8.5 kg m^{-2}. Table 2.10 shows the potential rates of C sequestered in the two thicket restoration sites. They concluded that the rate of C sequestration in restored thicket is likely to be as good as less water limited ecosystems such as forests, but can be achieved in a much more cost effective manner because start-up costs are low. They also recommended that *P. afra* cuttings could be used for restoration of thicket as high organic C levels (>5.5 %) have been reported by Mills *et al.* (2003b) in the top 10 cm of soil in the Eastern Cape.

Table 2.9 Carbon stocks in different vegetation types under different land use practices (Mills *et al.,* 2003b)

Vegetation type	Total carbon (t ha^{-1})
Thicket (intact thicket)	250
Grassland (Kikuyu)	170
Renosterveld	80
Karoo	30

Table 2.10 Potential rates of carbon sequestration (Mills & Cowling, 2006)

AREA	Carbon sequestered (kg C m^{-2})	Period of sequestration (years)
• Krompoort (Kirkwood)	11	27
• Adriens Vosloo Kudu Nature reserve (Grahamstown)	2.5	20

Mills & Cowling (2006) add that the benefits associated with C sequestration especially with the dominance of *P. afra* cuttings are:

- Improvement of biodiversity in the transformed area (revegetation with indigenous species)
- Carbon credit earnings on the international markets
- Decline of soil erosion
- Increase in wildlife carrying capacity

- Improvement in water infiltration and retention
- Offer employment to rural communities

The rate of soil organic carbon sequestration with adoption of recommended technologies actually depends on a number of factors which include soil texture and structure, rainfall, temperature, farming system and soil management. Strategies to increase the soil C pool include soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agroforestry practices, and growing energy crops on spare lands. Together with enhancing food security, C sequestration is likely to counterbalance fossil fuel emissions by 0.4 to 1.2 gigatons of C per year, or 5 to 15% of the global fossil-fuel emissions (Lal, 2004).

However, Mills *et al.* (2003b) state that the income that South African farmers may receive for C sequestration in the future actually depends on many factors such as:

- The amount of carbon that has been lost from virgin veld because of activities introduced by humans
- The time required for the restoration of the carbon that was lost
- The amount of land obtainable for carbon sequestration
- The price of carbon

Unfortunately, the price of C in future is reliant on decisions taken by the international community and thus South African landowners do not have power over it (Mills *et al.,* 2003b).

2.6 Modelling carbon stocks

Several models that can be used to estimate organic carbon content of soil have been developed or modified by researchers for this purpose. Each model is tailor-made depending on the type and amount of data available. Adaptations of some models were done to suite the objectives of a particular study. The following models are some of those that have been formulated throughout the years.

2.6.1 Pedo-transfer rules

With the absence of a properly compiled soil profile database based on analytical data for soil properties, organic carbon can be calculated by using pedotransfer rules. Darroussin & King (1996) define pedotransfer functions as predictive functions of certain soil properties from other easily routinely or cheaply measured properties. The authors go on to state that the advantages of this method are that interpretations are clear and they themselves can be updated whenever the need arises either if the soil database or the analysis data are improved. Table 2.11 shows the list of attributes of the soil profile database within the soil geographical database of Eurasia used in the pedotransfer rules. Organic carbon stocks were quantified using the existing data with reference to soil type, *i.e*. texture, structure, and classification in different provinces around the country. The relationship between these organic carbon data to land use was be taken into consideration as well as the relation of organic carbon stocks to soil forming properties such as climate, vegetation, relief and parent material.

The original pedotransfer rules were adapted by Van Ranst *et al.* (1995) (as cited by Jones *et al.,* 2004a) for calculating the organic carbon content of soils in Europe. These adapted rules were later refined by Jones *et al.* (2003) (as cited by Jones *et al.,* 2004a).

The effect of climate on organic carbon content was accounted for by applying a temperature correction ($TEMP_{cor}$) in the form of a mathematical function (Equation 2.2) of the type as done by Jones *et al.* (2004a):

$$TEMP_{cor} = f * cos(t_{AAAT})^{n} + c \qquad (2.2)$$

Where: AAAT is the average annual accumulated temperature above 0ºC

Based on the pedotransfer rules (PTR), Jones *et al.* (2005) developed a methodology identified as the PTR 21 to estimate organic carbon in the soils of Europe for policy support. Firstly after analyzing the existing conditions and removing any ambiguity, a basis of estimating topsoil organic carbon was set. Organic carbon in the topsoils was defined and the accumulated temperature parameter was removed completely from the conditions to be used for organic carbon estimations.

The revised PTR 21 ended up with five input parameters and 140 conditions. The parameters if well defined help in estimating the amount of soil organic carbon in a particular area whether low, medium or high as well as the range (in %) of organic carbon content. The second step was to account for the influence of temperature using a mathematical model (Equation 2.2).

Jones *et al.* (2005) stated that there are some limitations associated with this method. One limitation is clearly set by the number of conditions defined in the rule that the more parameters are used the more accurate the definition of the conditions to be used. Another disadvantage is the accuracy of the data used.

Table 2.11 List of attributes of the soil profile database within soil geographical database of Eurasia used in the pedotransfer rules (Darroussin & King, 1996)

Input attributes	**Input classes**
• Soil name (SN)	cf. (FAO, 1975) and (CEC, 1985)
• Topsoil texture class (TEXT)	1 Coarse (>0.5 mm) 2 Medium (0.25 – 0.5 mm) 3 Medium fine (0.10 – 0.25 mm) 4 Fine (0.002 – 0.10 mm) 5 Very Fine (<0.002 mm)
• Slope (S)	a Level (0-8%) b Sloping (8-15%) c Moderately steep (15-25%) d Steep (> 25%)
• Parent Material (PM)	cf. (CEC, 1985), (INRA-JRC, 1993)
• Land Use (U1)	cf. (CEC, 1985)
• Elevation (ZMIN, ZMAX)	cf. (INRA-JRC, 1993)
• Regrouped accumulated mean annual temperature class (ATC)	in meters

The main output attribute is shown in Table 2.12 together with input attributes and output classes associated with them for making the estimates.

Jones *et al.* (2004b) uses PTR21 defined by Van Ranst *et al.* (1995) (as cited by Jones *et al.,* 2004b). Six input parameters (three for soil, one each for texture, land use and temperature) are used to estimate organic carbon in the topsoil horizon. Jones *et al.* (2004b) further show examples of the 'if-then' conditions in Table 2.13 that comprise this rule, with a total of 150 conditions being defined.

Table 2.12 List of selected output attributes from pedotransfer rules with their required inputs (Darroussin & King, 1996)

Output attributes	Input attributes	Output classes
Topsoil organic carbon content (OC_TOP) (0-250 mm)	Soil name - (FAO, 1975) and (CEC, 1985) TEXT -Topsoil textural class USE - Regrouped land use class ATC - Accumulated mean temp	H(igh): > 6.0% M(edium): 2.1-6.0% L(ow): 1.1-2.0% V(ery) L(ow): < 1.0%

The translation of condition 37 (Table 2.13) is as follows:

If (SN1=L) and (SN2=c) and (TEXT=2) and (USE=C) and (ACT=M) then let OC_TOP=L.

Jones *et al.* (2004a) also mentions that the revised PTR for organic top soils uses % input parameters instead of the 6 parameters in the original PTR 21. Temperature was removed from the conditions because it is taken into account through the correction coefficient ($TEMP_{cor}$).

So far the PTR 21 has been adapted for estimating the organic carbon content of the topsoils in Europe. For the rules to apply in South Africa certain adjustments have to be made to suite the conditions found here. For example the soil classification system for South Africa will be used and the input parameters will be determined by the number of parameters available in the data which will in turn determine the number of conditions available.

Table 2.13 Selected conditions from PTR 21 for topsoil organic carbon (Jones *et al.,* 2004b)

Co	SN1	SN2	SN3	TEXT	USE	ATC	OC
35	L	g	*	*	SN	M	M
37	L	c	*	2	C	M	L
85	J	t	*	2	SN	*	H
117	O	*	*	*	*	*	H

Where:

Co = condition number; * - 'wild card'

SN1 = FAO soil group code (e.g. L Luvisol)

SN2 = FAO soil subgroup code (e.g. g gleyic)

SN3 = FAO soil subgroup (2^{nd}) code (e.g. s stagnic in Lgs)

TEXT = FAO texture class (1 coarse – 5 very fine)

USE = Land use class (C cultivated, SN semi natural)

ATC = Accumulated temperature (L low, M medium, H high)

OC = OC_TOP class (L, M, H- see below for limits)

2.6.2 Water erosion prediction project model

According to Brejda *et al.* (2001) there is a relationship between soil organic carbon, bulk density, and soil depth. In a study done on private lands in the United States of America, they started by calculating the soil bulk density (ρ) for each sample point using the bulk density algorithm provided in the water erosion prediction project model (Alberts *et al.,* 1995)(as cited by Brejda et al., 2001), namely:

$$\rho = [1.514 + 0.25(\text{sand}) - 13.0(\text{sand})(\text{OM}) - 6.0(\text{clay})(\text{OM}) - 0.48(\text{clay})(\text{CEC}_r)] \qquad (2.3)$$

where sand and clay are the sand and clay fraction of the sample, ranging from 0 to 1; OM is the organic matter content of the sample which is calculated as OC x 1.69; and CEC_r is the ratio of the CEC of the clay (CEC_c) to the clay content of the soil, which is calculated using Equation 2.4.

$$CEC_c = CEC – OM(142 + 170D) \qquad (2.4)$$

and D is the sampling depth (meters).

The soil organic carbon mass in each sample was calculated by multiplying the calculated bulk density value by the organic carbon concentration and soil depth.

2.6.3 Rothamsted carbon model

The Rothamsted carbon model (RothC) was used by Cerri *et al.* (2003) in modelling soil carbon from forest and pasture ecosystems of the Amazon, Brazil. RothC is described in detail by Coleman *et al.* (1997). The model calculates the turnover of organic C in non-waterlogged topsoils based on moisture content, soil type, plant cover and temperature. This model does not necessarily estimate the amount of soil organic carbon but it replicates trends in soil organic carbon. In this model, soil organic carbon is divided into four active fractions and one small inert organic matter (IOM) fraction. The four active fractions are resistant plant material (RPM), decomposable plant material (DPM), humified organic matter (HUM), and microbial biomass (BIO). Each fraction decomposes by a first-order process with its own particular rate. The IOM fraction is able to withstand decomposition.

The model can be fitted with measurements of organic carbon from diverse samples. RothC is only concerned with soil processes. The RothC model's main advantage is that it operates with data that are readily obtainable. In order to commence the RothC model, the IOM content of the soil, should be known. It can be estimated by the model from soil radiocarbon data, but because it is costly to obtain IOM values, they can be approximated from the total soil organic carbon content without considering the soil type, climate or land use (Falloon *et al.,* 1998).

2.6.4 Multifactorial approach

This method was used by Krishnan *et al.* (2007) in India. They developed a model relating soil organic carbon stocks to the different environmental factors that control soil organic carbon levels, especially land cover. This method is similar to the one described earlier in Section 2.6.2 where soil organic carbon was estimated using estimated soil bulk density values. In principle this method is based on the theory of soil genesis which was developed by Jenny (1941) which states that the soil (S) is a function of climate *(cl),* organisms *(o),* topography *(r),* parent material *(p),* and time *(t)*:

$$S = f\,(cl, o, r, p, t) \tag{2.5}$$

The factors that control the levels of soil organic carbon are rainfall, temperature, pH, soil texture, and the type of vegetation (Jenny *et al.,* 1948). Krishnan *et al.* (2007) obtained data from a soil resource inventory and complemented it with environmental data to estimate as well as map the soil organic carbon stocks at regional level. They produced a model that linked soil organic carbon stocks to the different environmental factors that control the levels of organic carbon in the soil.

For this study Equation 2.5 was modified to give soil organic carbon stock in terms of environmental and soil parameters for which maps are either available or can be prepared easily using existing data as shown by Equation 2.6:

SOC stock = *f* (bioclimate, physiography, altitude, soil, rock, land cover) (2.6)

Data-mining methods were applied to a soil profile database to solve equation 2.5 and GIS facilities to compute solutions for the entire study area (Krishnan *et al.,* 2007). The soil organic carbon stock of each profile was calculated for the top 300 mm depth as the sum of the soil organic carbon stock of the different horizons (1, 2 or 3) sampled in the 300 mm. For each horizon, soil organic carbon stock (g m^{-2}) was calculated by multiplying the organic carbon content (g g^{-1}) by the bulk density (g m^{-3}) and by the thickness (m) of the horizon.

This method also caters for missing bulk density data. For the remaining horizons with missing values of bulk density another generic model (Equation 2.7) was proposed and solved using a recent data-mining method.

BD = *f* (soil type, horizon, land cover, C , texture, gravel) (2.7)

The multiple additive regression tree (MART) method by Friedman (2001) was the data-mining method that was selected to solve equations 2.5 and 2.6. Soil taxa, horizon type, texture (clay, silt, sand and gravel contents) type of land cover, and organic carbon content of the horizon were used as predictor variables for the completion of the bulk density model for the horizons with data (BD data). The model of soil organic carbon stock was constructed using ten soil and environmental parameters namely: soil type, texture, gravel, altitude, geomorphology, land cover, geological substrate, rainfall, temperature, and number of dry months (Krishnan *et al.,* 2007). This method can be considered as an improvement over existing methods for evaluating soil organic carbon stock over large areas.

2.6.5 Introductory carbon balance method

The introductory carbon balance method (ICBM) was developed by Andrén & Kätterer (1997) as a soil C model that can be used over a 30 year time period with 1 year time steps. The ICBM was done using data from a Swedish long-term experiment. The parameters used in this model can be estimated from readily available data such as soil type, climate, and crop. This model can therefore be used to make sound estimates concerning soil organic matter dynamics which are caused by management and climate.

Sites from Germany and Great Britain were selected, as well as an experimental period of more than 8 years and known initial soil C content. The sites were of different management practices. The soil bulk density values were needed to change C concentrations to a mass base. Equation 2.8 was used to estimate bulk density where it was not reported especially for soils in England and Wales. The known depth of the topsoil (*i.e.* top layer down to the ploughing depth) was used to calculate topsoil C mass on an areal base of g m^{-2}. The depth of the topsoil was assumed to be 250 mm where it was unknown (Kätterer & Andrén, 1999).

$$\text{Bulk density} = 1.3 - (0.274 \log \%C) \tag{2.8}$$

The ICBM consists of two state variables, young (*Y*) and old (*O*) organic material. This model was used to predict soil C dynamics between the start and the end of the experiments but when preliminary conditions are too far away from steady-state the simple model structure becomes inadequate (Andrén & Kätterer, 1997).

2.6.6 Global environment facility soil organic carbon modelling system

To predict soil C stocks and changes in the Brazilian Amazon during the period between 2000 and 2030, Cerri *et al.* (2007) used the global environment facility soil organic carbon modelling system (GEFSOC). This model was used to integrate data and conduct analysis with three well-recognized models and methods namely: the Century general ecosystem model, the RothC soil decomposition model and the intergovernmental panel on climate change (IPCC) method used for assessing soil organic C at regional scales. This modelling system requires six basic data classes to build the datasheets necessary for a regional simulation. The data classes include native vegetation, soils and latitude/longitude, climate, historic and current land use management. The results were presented in a map, table and graph form for the entire Brazilian Amazon. The results showed a decline in soil organic carbon in all the methods that were used for the period under study. The Century and RothC methods revealed that the 1990 values were 7% higher than the 2030 values.

2.6.7 Digital soil mapping approach

Grimm *et al.* (2008) used the digital soil mapping approach to predict the spatial distribution of soil organic carbon in Panama. This approach relies on a soil inference model based on spatially referenced environmental layers of topographic attributes, soil units, parent material, and forest history. After taking samples at different levels they were analysed for soil organic carbon by dry combustion. Soil organic carbon stocks *i.e.* carbon mass per unit area for a given depth, was calculated using Equation 2.9.

$$SOC_{stock} = SOC_{conz} \times \rho \times (1\text{-}ST) \times \Delta d \times UFC \qquad (2.9)$$

Where: SOC_{stock} = soil carbon stock (kg ha^{-1})

SOC_{conz} = soil carbon concentration (%)

ρ = bulk density of fine earth (kg m^{-3})

ST = stoniness, volumetric percentage volume (vol.%)

Δd = thickness of the layer (m)

UFC = a unit conversion factor (100 m^{2} ha^{-1})

The Random Forest (RF) analysis was used as a modelling tool on the soil organic carbon data for each depth interval. “The RF based digital soil organic carbon mapping approach gave soil organic carbon estimates of high spatial resolution as well as error and predictor importance”. The topographic attributes were the environmental attributes that explained most of the variation in the topsoil (0-100 mm). In the subsoil (100-500 mm) soil organic carbon distribution was better explained by soil texture classes as deduced from mapping units. They concluded that the digital mapping approach can be used in similar landscapes to improve the spatial distribution of soil organic carbon estimates (Grimm *et al.,* 2008).

2.6.8 Regression equation approach

The relation of soil organic matter content to climate and altitude was investigated by Dai & Huang (2006). They had a total of 886 data sets which were completed around the early 1980's and distributed in six geographical regions of China. These regions were classified according to climate gradient and vegetation community succession. The key factors that control surface soil organic matter concentration were found in the geographical regions. The data collected included the depth of surface soil (A horizon), percentage of cultivated profiles, annual mean precipitation, annual mean temperature, and altitude.

To test the significance of the means of soil organic matter concentration, a one-way analysis of variance (ANOVA) and Fisher's Least Significant Difference (LSD) was used. A simple correlation analysis was used to measure the relationship between the concentration of soil organic matter and mean annual temperature, mean annual precipitation, and altitude. A partial correlation analysis was used to identify the influence of precipitation, temperature, and altitude on soil organic matter concentration. To find the best predictive models for soil organic matter in the whole country, a linear multiple regression (forward stepwise) was used. The SPSS software 12.0 was used for statistical analysis (Dai & Huang, 2006).

To fit the relationships between annual mean temperature and annual mean precipitation, and altitude, a linear function and two non-linear functions of power and exponential were used. The two non-linear functions were changed logarithmically to corresponding linear functions. The exponential function was the best in describing the relationship and therefore used to do the simple and partial correlation analysis. The partial correlation analysis was done for separating the effects of temperature, precipitation, and altitude. A partial correlation coefficient is used to measure the correlation between any two variables when other variables are held constant. After close examination of the partial correlation coefficient in comparison with the simple correlation, the results revealed that the surface soil organic matter concentration in zonal soils of China is mainly influenced by climatic factors which are precipitation and temperature. However, the impact of altitude on soil organic matter might be indirectly conveyed through temperature and precipitation (Dai & Huang, 2006).

2.6.9 Soil and terrain database approach

Soil carbon stocks of Central Africa were mapped using the soil and terrain database (SOTER) by Batjes (2008). The countries included Burundi, Rwanda, and the Democratic Republic of Congo. To derive the landform units and to generate terrain information, Space Shuttle Radar Topographic Mission (SRTM) digital elevation data at 90 m resolution were used. The geological maps, profile data, and soil survey reports were used to describe and differentiate the individual SOTER (map) units. Most profiles from the different countries were under indigenous vegetation, which corresponds with baseline circumstances (Batjes, 2008).

Around 84% of the horizons had available soil organic carbon data, classified data on volume fragments >2 mm for 92% of the horizons and only 1% of bulk density data. Gaps in the measured data are usually filled using expert rules and pedotransfer rules. Batjes (2007) states that the basic procedure considers the FAO soil unit name, soil textural class, soil variable, and depth of the layer. The relationship between temperature, precipitation, and vegetation characteristics, which all highly affect soil organic matter levels, was used as a basis for the agroclimatic zones for Central Africa. They were then used for overlay with the soil and terrain layer. The resulting ecoregions were then used for the estimation of soil organic carbon stocks. With the main emphasis being put on median values of soil organic carbon with 95% confidence limits, the results included a map on the area-weighted organic carbon content in the soils of Central Africa (Batjes, 2008).

2.6.10 Inverse distance weighting method

The land type survey in South Africa started in 1970 and 2380 profiles were analysed morphologically and chemically (Land Type Survey Staff, 2003). The land type survey utilized the binomial soil classification system (MacVicar *et al*., 1977).

Barnard (2000) used the data and created a generalized map for the C content of virgin topsoils in South Africa. Organic carbon was analysed for the samples. A correction factor of 1.3 was used in the calculations to obtain organic carbon (Non-Affiliated Soil Analysis Committee, 1990). The C values were then interpolated using the inverse distance weighing method (IDW) making use of the nearest neighbours at a power of 2. The cell sizes for the interpolated grid for South Africa were 5000 m x 5000 m. The resultant distribution of organic carbon generally followed the rainfall distribution of South Africa.

Barnard (2000) also concluded that the relationship between soil organic carbon and rainfall is very weak with a correlation coefficient value of 58.6% between them and -28.9% between soil organic carbon and maximum temperature. The two independent variables explain 35.4% of the variability (Equation 2.10).

$$C = 1.706367 - 9.211789e^{-02} \times MaxT - 3.328433e^{-03} \times Rain \tag{2.10}$$

There is a positive correlation between rainfall and carbon. On the contrary, as maximum temperatures decrease C values increase. The national land cover database was used to separate points into four classes namely natural vegetation, cultivated dryland, plantations and cultivated irrigation. The correlation between C and associated independent values was then established. These variables included maximum temperature, minimum temperature, rainfall, clay, longitude, and latitude. It was also noted that multi-linear regression models to interpolate C countrywide were not adequate for being used to develop a spatial interpolation of C across the country (Barnard, 2000).

2.7 Estimating soil bulk density

The bulk density of soil can be explained as the weight of a given volume of soil in its natural condition (Briggs, 1977) and is vital for the estimation of soil organic carbon stocks. Most of the models that were formulated for the modelling of soil organic carbon stocks include the input of soil bulk density data. For instance, Batjes (2008) estimated the carbon content of the soil by volume (kg C m^{-2} to a pre-defined depth) for each profile. He calculated it according to bulk density, proportion of carbon, thickness of layer and volume of the fragments >2 mm. The strong relationship between soil carbon and soil bulk density was shown in the results where Batjes (2008) discovered that in most soils, the highest soil carbon values were linked with low bulk density values and *vice versa*. Unfortunately, there are many gaps in soil analytical databases probably due to the intensive laborious task involved in soil bulk density sampling and analysis. However, some scientists have tried to come up with different models that could be used for estimating soil bulk density using other measured soil properties.

Rawls (1983) simply explained the bulk density of the soil as the impact of soil management practices on soil properties that in turn affect the movement and retention of water in the soil. Soil texture and organic matter are the chief manipulators of bulk density. Rawls (1983) developed a method for predicting bulk density using collected soil survey information of particle size and organic matter. The research was based on the fact that the amount of organic matter had a significant impact on the bulk density of the soil.

A contour programme using all the data was used to develop a mineral density map based on the percentages of sand and clay. The bulk density of the mineral matter was derived from the map. The contour map of standard deviations of the bulk density of the mineral matter was also derived. Equation 2.11 was used to calculate the soil bulk density (Rawls, 1983).

$$\text{Soil bulk density} = 100/[(\%OM/OMBd) + (100 - \%OM)/MineralBb)] \qquad (2.11)$$

Where OM = Organic matter (%) and Bd = Bulk density (g cm^{-3})

In conclusion this method can be used to predict the bulk density of natural undisturbed soils based on the sand, clay, and organic matter percentages. This method is very important when particle size information and organic matter content is available for the estimation of the soil bulk density (Rawls, 1983).

Pedotransfer functions or regression models are a good way for estimating soil bulk density using measured soil properties. Benites *et al.* (2007) estimated soil bulk density from existing soil survey reports in Brazil. After a series of steps and statistical analysis a simplified regression relationship between soil properties and bulk density for all soils revealed that clay, total organic carbon, and the sum of basic cations had the highest correlations (Table 2.15).

Table 2.15 Simplified regression relationships between soil properties and bulk density for all Brazilian soils (number of observations = 1396) (Benites *et al.*, 2007)

Model	Intercept	Clay	TOC[1]	SB[2]	Adjusted R^2	SE[3]
1	1.5600	-0.0005	-0.0100	0.0075	0.66	0.11
2	1.5688	-0.0005	-0.0090		0.63	0.11
3	1.5224	-0.0005			0.42	0.14

[1]TOC = Total organic carbon, [2]SB = Sum of basic cations, [3]SE = Standard error of the estimate

They concluded that regression relationships are viable for predicting bulk density from other soil properties in Brazilian soils. The variation of 66% of bulk density at all soil depths was described by Model 1 (Table 2.15) which is a simplified regression model using only organic carbon, clay and the sum of basic cations. They also added that this model was less biased, more precise and more accurate.

Manrique and Jones (1991) investigated the relationship between the bulk density of the soil and the physical and chemical properties of the soil. While modelling soil bulk density they examined the multiple regression relationships between bulk density and soil physical and chemical properties. They found that bulk density was significantly inversely related to organic carbon. Meermans *et al.* (2008) used the regression equation developed by Manrique and Jones (1991) which only uses soil organic carbon as an input variable to calculate bulk density (Equation 2.12).

$$\rho_s = 1.66 - 0.318 \times \sqrt{SOC} \qquad (2.12)$$

Where ρ_s = Soil bulk density

2.8 Conclusions

This literature review shows that there is still a lot of work that has to be done on soil organic carbon in South Africa. The research that has been done so far proves that there is a decline in the amount of soil organic carbon in South Africa as well as worldwide. Drastic measures have to be taken to conserve the remaining organic carbon sinks. With the intensifying of agricultural systems involving high inputs of chemical fertilizers, synthetic pesticides, hybrid seeds and mechanical irrigation systems this leads to a decline in the fertility status of soil. These activities may also result in the increase in the carbon content found in the atmosphere which causes global warming, which is a universal problem. Action has to be taken to mitigate the dangers that are being caused by the loss of carbon in the soil.

The common practices that lead to soil organic matter loss are tillage, intensive grazing, deforestation and frequent burning which is practised in grassland farming. In the absence of these practices, soil erosion is decreased exponentially with depth, which means that the topsoil is conserved, which is the richest in organic matter. The purpose of increasing soil organic carbon by either increasing organic matter inputs to the soil, decreasing decomposition of soil organic matter and the oxidation of soil organic carbon is highly recommended. This can be done by reducing tillage intensity, decreasing or ceasing the fallow period, using a winter cover crop, changing from monoculture to rotation cropping, or altering soil inputs to increase primary production (e.g. manuring, fertilizers, pesticides, and irrigation). Reverting cultivated lands to perennial vegetation cover such as grasslands could help reduce the loss of soil organic carbon. If cultivation is not ceased, conservation tillage should be practised. This can be achieved by leaving crop residues *i.e.* mulch on the soil surface. This reduces the amount of topsoil that can be eroded as well as supplying plant residues which decompose and increases the amount of soil organic matter. The plant residues that are left as mulch conserve moisture and therefore aid in lowering the temperature of the soil. All these factors slow down the decomposition of soil organic matter and allow the accumulation of soil organic carbon. The sugarcane industry found that trash retention and annual fertilizer applications have substantially positive long-term effects on soil organic carbon by increasing biomass production.

Most of the soil organic matter and soil organic carbon losses are attributed to the change of land use from natural to agricultural ecosystems. These losses are accelerated by elements of climate such as precipitation as well as high temperatures which increase the rate of decomposition of soil organic matter. This implies that the rate of soil organic carbon loss depends highly on climate with the warmer drier areas having less soil organic carbon than the cooler wetter areas. Irrigation and fertilization have been reported to increase soil organic carbon in areas under cultivation. This is because there is an increase in biomass production which contributes positively to the levels of organic matter in the soil. Soil C availability reduces clay dispersion and therefore maintains soil structure thus improving both the chemical and physical properties of the soil. Management of soil organic carbon should be optimized and all practices that contribute positively towards its conservation and sequestration should be taken into account.

However, to draw up mitigation strategies on how to conserve soil organic carbon in South Africa, its current status should be well documented. Evidence has been provided that proves soil organic carbon is decreasing at an alarming rate. Fortunately, organic carbon is in most cases of soil analysis one of the parameters that are measured. More information on soil organic carbon needs to be established that would provide a comprehensible view on the soil organic carbon status in South Africa as well as relating it to other important soil parameters.

CHAPTER 3
DATA COLLECTION AND PROCESSING

The estimation of soil organic carbon content in South African soils is very important for soil fertility, soil protection and mitigation strategies for global warming. Therefore, an accurate picture of the organic carbon status in South African soils should be put into place as well as the land management practices that would have the greatest effect in preventing the depletion as well as restoration of soil organic carbon.

The primary source of data for this study was taken from the Memoirs of the Agricultural Natural Resources of South Africa which was compiled by the Department of Agriculture in Pretoria (Land Type Survey Staff, 2003). The land type survey started in 1970 and was founded on the theory of land types. Each land type displays a certain level of uniformity in terms of terrain morphology, climate and soil pattern. A number of land soil profiles, called modal profiles were chosen to signify the range of soils encountered in the survey (Department of Agriculture and Water Supply, 1986). Approximately 2 200 profiles all over South Africa were sampled and analysed for physical and chemical properties as shown in Table 3.1. Other soil surveys were also used to supplement the physical and chemical data from the profiles. The South African Binomial Soil Classification System (MacVicar *et al.,* 1977) was used for the land type survey whilst the South African Taxonomical Soil Classification System (Soil Classification Working Group, 1991) was utilized for the later soil surveys. All the physical and chemical data from the soil surveys were captured in a MS Access database by the ARC-Institute for Soil, Climate and Water in Pretoria.

The memoirs were accompanied by 1:250 000 scale land type maps as well as modal soil profile data and soil profile analysis. Each of the land types displays a marked uniformity in terms of climate, terrain form, and soil pattern. The analytical data for each profile were contained in the memoir that dealt with the land inventories for the particular 1:250 000 map and is available electronically in a database.

The data was received in a form of two tables namely: the physical properties table and the chemical properties table, both in Microsoft Excel (2003) spreadsheets. Main emphasis was put on the parameters that affect the level of organic carbon in soil. Table 3.3 shows the key parameters selected for use in this study.

Table 3.1 Physical and chemical soil properties analysed for the land type modal profiles

Physical properties	Chemical properties
• Particle size distribution	• Total exchangeable acidity and exchangeable aluminium
• Air to water permeability ratio	• Exchangeable and soluble cations, cation exchange capacity, titratable acidity and electrical conductivity
• Modulus of rupture	• Soil pH
• Water retentivity	• Electrical resistance of the saturated paste
• Dispersion ratio	• Organic carbon
	• Phosphorus status
	• Phosphorus sorption
	• Micronutrients (Cu, Mn, Zn, Co, and B)

The profiles were thoroughly described in the memoirs. Table 3.2 shows a list of attributes included in the profile description.

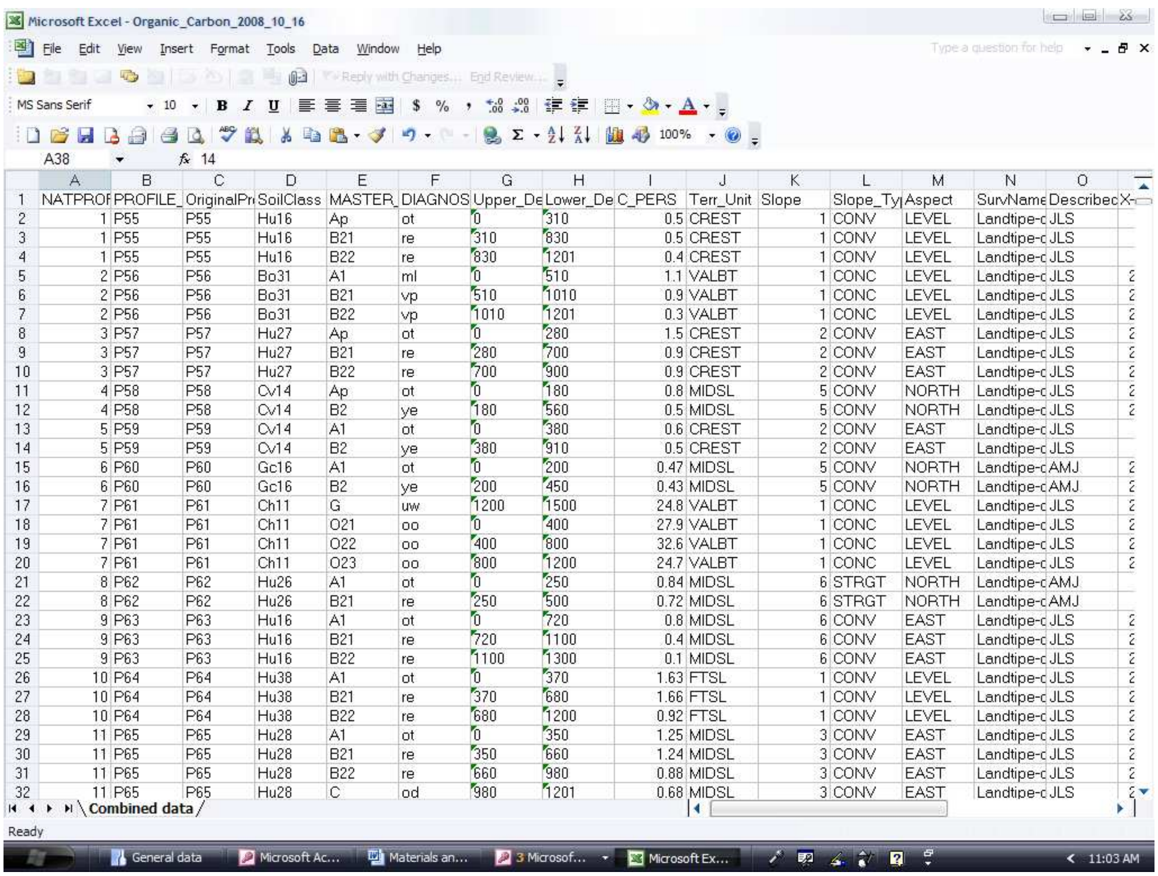
Table 3.2 Profile description attributes available in the land type memoirs

• Profile number	• Soil form
• Land type map	• Soil series
• Latitude/Longitude	• Terrain morphological unit
• Land type number	• Slope percentage
• Elevation	• Slope shape
• Climate zone number	• Slope aspect
• Vegetation	• Water table
• Parent and underlying materials	• Stoniness
• Master horizons, diagnostic horizons and depths	• Erosion
• Moisture content	
• Colour	

The two tables (physical and chemical) were thus combined and the related data was extracted from the database using Microsoft Access (2003). An example of the results is given in Figure

3.1 and these data helped to produce background data for the evaluation of the current carbon stocks in South Africa. The process of data processing is explained later.

Unfortunately, an inconsistency in the classification of the diagnostic horizons was discovered in the land type survey database. In some instances soil forms were used therefore to classify diagnostic horizons. To be consistent a list of underlying materials (subsoils) was compiled in order to help fill in the gaps (Table 3.4). The designations of the diagnostic horizons and underlying materials are described in Table 3.5. All the horizons with missing data and inadequate information for classification as well as those without soil organic carbon data were deleted from the database. The samples were taken mainly from virgin soils. Approximately, 11 640 samples contained usable data.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
1	NATPROF	PROFILE_	OriginalPr	SoilClass	MASTER_	DIAGNOS	Upper_De	Lower_De	C_PERS	Terr_Unit	Slope	Slope_Ty	Aspect	SurvName	Describec	X-
2	1	P55	P55	Hu16	Ap	ot	0	310	0.5	CREST	1	CONV	LEVEL	Landtipe-c	JLS	
3	1	P55	P55	Hu16	B21	re	310	830	0.5	CREST	1	CONV	LEVEL	Landtipe-c	JLS	
4	1	P55	P55	Hu16	B22	re	830	1201	0.4	CREST	1	CONV	LEVEL	Landtipe-c	JLS	
5	2	P56	P56	Bo31	A1	ml	0	510	1.1	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
6	2	P56	P56	Bo31	B21	vp	510	1010	0.9	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
7	2	P56	P56	Bo31	B22	vp	1010	1201	0.3	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
8	3	P57	P57	Hu27	Ap	ot	0	280	1.5	CREST	2	CONV	EAST	Landtipe-c	JLS	2
9	3	P57	P57	Hu27	B21	re	280	700	0.9	CREST	2	CONV	EAST	Landtipe-c	JLS	2
10	3	P57	P57	Hu27	B22	re	700	900	0.9	CREST	2	CONV	EAST	Landtipe-c	JLS	2
11	4	P58	P58	Cv14	Ap	ot	0	180	0.8	MIDSL	5	CONV	NORTH	Landtipe-c	JLS	2
12	4	P58	P58	Cv14	B2	ye	180	560	0.5	MIDSL	5	CONV	NORTH	Landtipe-c	JLS	2
13	5	P59	P59	Cv14	A1	ot	0	380	0.6	CREST	2	CONV	EAST	Landtipe-c	JLS	
14	5	P59	P59	Cv14	B2	ye	380	910	0.5	CREST	2	CONV	EAST	Landtipe-c	JLS	
15	6	P60	P60	Gc16	A1	ot	0	200	0.47	MIDSL	5	CONV	NORTH	Landtipe-c	AMJ	2
16	6	P60	P60	Gc16	B2	ye	200	450	0.43	MIDSL	5	CONV	NORTH	Landtipe-c	AMJ	2
17	7	P61	P61	Ch11	G	uw	1200	1500	24.8	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
18	7	P61	P61	Ch11	O21	oo	0	400	27.9	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
19	7	P61	P61	Ch11	O22	oo	400	800	32.6	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
20	7	P61	P61	Ch11	O23	oo	800	1200	24.7	VALBT	1	CONC	LEVEL	Landtipe-c	JLS	2
21	8	P62	P62	Hu26	A1	ot	0	250	0.84	MIDSL	6	STRGT	NORTH	Landtipe-c	AMJ	
22	8	P62	P62	Hu26	B21	re	250	500	0.72	MIDSL	6	STRGT	NORTH	Landtipe-c	AMJ	
23	9	P63	P63	Hu16	A1	ot	0	720	0.8	MIDSL	6	CONV	EAST	Landtipe-c	JLS	2
24	9	P63	P63	Hu16	B21	re	720	1100	0.4	MIDSL	6	CONV	EAST	Landtipe-c	JLS	2
25	9	P63	P63	Hu16	B22	re	1100	1300	0.1	MIDSL	6	CONV	EAST	Landtipe-c	JLS	2
26	10	P64	P64	Hu38	A1	ot	0	370	1.63	FTSL	1	CONV	LEVEL	Landtipe-c	JLS	2
27	10	P64	P64	Hu38	B21	re	370	680	1.66	FTSL	1	CONV	LEVEL	Landtipe-c	JLS	2
28	10	P64	P64	Hu38	B22	re	680	1200	0.92	FTSL	1	CONV	LEVEL	Landtipe-c	JLS	2
29	11	P65	P65	Hu28	A1	ot	0	350	1.25	MIDSL	3	CONV	EAST	Landtipe-c	JLS	2
30	11	P65	P65	Hu28	B21	re	350	660	1.24	MIDSL	3	CONV	EAST	Landtipe-c	JLS	2
31	11	P65	P65	Hu28	B22	re	660	980	0.88	MIDSL	3	CONV	EAST	Landtipe-c	JLS	2
32	11	P65	P65	Hu28	C	od	980	1201	0.68	MIDSL	3	CONV	EAST	Landtipe-c	JLS	2

Figure 3.1 An example of the combined physical and chemical data tables

Table 3.3 Physical and chemical properties of soil samples in the land type database

Parameters	Units
• Master horizons	O A E B G C R
• Diagnostic horizons	ah ml ot ve oo al db gc gs gh hp lc nc ne od om on pr pz re ro rs sc so sp ud uw vp vr ye
• Organic carbon	%
• Rainfall	mm
• Evaporation	mm
• Aridity index	
• Clay	%
• Terrain morphological units	Crest Scarp Midslope Footslope Valley bottom
• Slope percentage	%
• Slope type	Convex Concave Straight
• Slope aspect	North South East West Level North west South west North east South east West south west

Table 3.4 Soil forms and underlying materials

Soil forms	Underlying materials
Addo (Ad)	sc
Arcadia (Ar)	od
Augrabies (Ag)	on
Avalon (Av)	on
Bloemdal (Bd)	on
Bonheim (Bo)	ud
Bainsvlei (Bv)	on
Cartef (Cf)	so
Constantia (Ct)	od
Champagne (Ch)	on
Clovelly (Cv)	od
Dundee (Du)	al
Escort (Es)	od
Fernwood (Fw)	od
Griffin (Gf)	od
Glenrosa (Gs)	so
Houwhoek (Hh)	so
Hutton (Hu)	od
Inanda (Ia)	od
Inhoek (Ik)	al
Katspruit (Ka)	on
Kimberley (Ky)	od
Kroonstad (Kd)	on
Kranskop (Kp)	od
Longlands (Lo)	on
Lamotte (Lt)	uw
Magwa (Ma)	od
Mispah (Ms)	ro
Milkwood (Mw)	ro
Mayo (My)	so
Nomanci (No)	so
Oakleaf (Oa)	od
Pinedine (Pn)	on
Rensburg (Rg)	on

Table 3.4 Continued…

Soil forms	Underlying materials
Shortlands (Sd)	od
Shepstone (Sp)	od
Sterkspruit (Ss)	od
Swartland (Sw)	so
Sweetwater (Sr)	od
Tambankulu (Tk)	on
Valsrivier (Va)	ud
Vilafontes (Vf)	od
Wasbank (Wa)	od
Westleigh (We)	on
Willowbrook (Wo)	on

The land type survey data was structured per master horizon and per diagnostic horizon. Master horizons were found to be A1, A2, AB, B, B1, B2, B3, C, E, G, O, R, and X. It was decided that X (where n=6) should be discarded or deleted because there were no diagnostic characteristics which would help characterise the samples or horizons.

Standard error bars were drawn to test whether the difference in organic carbon content between the layers was significant or not. Overlapping of the standard error bars meant the horizons were not significantly different from each other and *vice versa* (Cumming *et al.,* 2007). The length of the error bars also reveals the amount of variation available in the data.

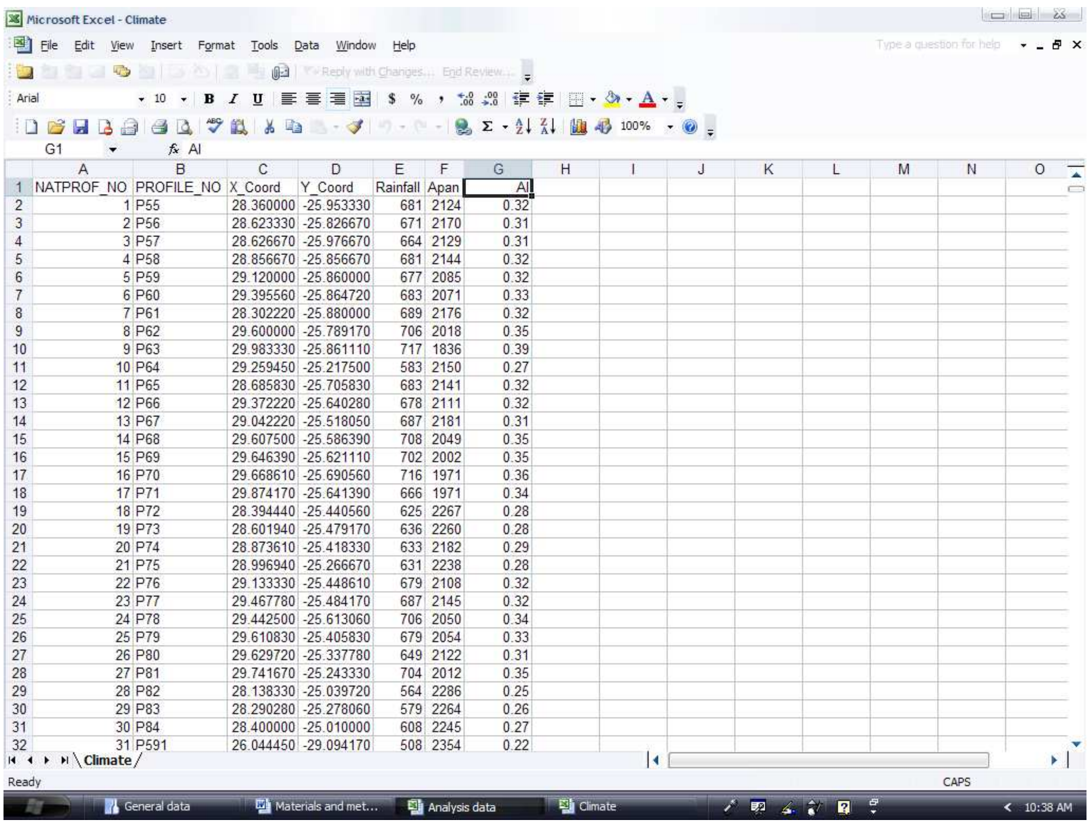
The A1 and AB were combined as AB which is defined as a transition horizon between the A and B and it corresponds most closely with the A as a master horizon (Soil Classification Working Group, 1991). With the help of standard error bars B, B1, B2, and B3 were treated as B as well as A2 as E. During the process of organizing the data, there was evidence of some missing data. Concentration was then focussed on the available data. In total there were 7 master horizons namely; O, A, E, B, G, C, and R. There were 30 diagnostic horizons and underlying materials as shown in Table 3.5. The average, maximum, minimum and standard deviation, standard error, 25th and 75th percentile of the organic carbon content of the horizons were calculated for every master and diagnostic horizon.

Table 3.5 Abbreviations for diagnostic horizons and underlying materials (Soil Classification Working Group, 1991)

Designation	Description
oo	organic material
ah	humic
ve	vertic
me	melanic
ot	orthic
gs	E horizon
gc	gleycutanic B
gh	G horizon
al	stratified alluvium
db	dorbank
hc	hardpan carbonate
hp	hard plinthic B
lc	lithocutanic B
nc	neocarbonate B
ne	neocutanic B
od	unspecified dry material
on	unspecified material with signs of wetness
om	unknown symbol
pr	prismacutanic B
pz	podzol B
re	red apedal B
ro	hard rock
rs	regic sand
sc	soft carbonate
so	saprolite
sp	soft plinthic B
ud	unconsolidated material without signs of wetness
uw	unconsolidated material with signs of wetness
vr	red structured B
ye	yellow-brown apedal B

Microsoft Access (2003) was used to create new appropriate data spreadsheets that would be applicable in estimating organic carbon stocks in South Africa. During the process an additional data table was created which integrated the climate data (Figure 3 2) and the land type survey data. Climate elements that affect the amount of organic carbon content of the soil are precipitation (P), evaporation (E), and aridity index (AI = P/E). The climate data was taken from the South African Atlas of Climatology and Agrohydrology (Schulze, 2006).

With the profile numbers being the common identifying factor, the land type survey data was combined with climate data using Microsoft Access 2003. Graphs were then drawn using Microsoft Excel 2003 to determine the relationship between soil organic carbon and the elements of climate namely rainfall, evaporation, and aridity index. The correlation index (R^2) was determined using Microsoft Excel 2003.



NATPROF_NO	PROFILE_NO	X_Coord	Y_Coord	Rainfall	Apan	AI
1	P55	28.360000	-25.953330	681	2124	0.32
2	P56	28.623330	-25.826670	671	2170	0.31
3	P57	28.626670	-25.976670	664	2129	0.31
4	P58	28.856670	-25.856670	681	2144	0.32
5	P59	29.120000	-25.860000	677	2085	0.32
6	P60	29.395560	-25.864720	683	2071	0.33
7	P61	28.302220	-25.880000	689	2176	0.32
8	P62	29.600000	-25.789170	706	2018	0.35
9	P63	29.983330	-25.861110	717	1836	0.39
10	P64	29.259450	-25.217500	583	2150	0.27
11	P65	28.685830	-25.705830	683	2141	0.32
12	P66	29.372220	-25.640280	678	2111	0.32
13	P67	29.042220	-25.518050	687	2181	0.31
14	P68	29.607500	-25.586390	708	2049	0.35
15	P69	29.646390	-25.621110	702	2002	0.35
16	P70	29.668610	-25.690560	716	1971	0.36
17	P71	29.874170	-25.641390	666	1971	0.34
18	P72	28.394440	-25.440560	625	2267	0.28
19	P73	28.601940	-25.479170	636	2260	0.28
20	P74	28.873610	-25.418330	633	2182	0.29
21	P75	28.996940	-25.266670	631	2238	0.28
22	P76	29.133330	-25.448610	679	2108	0.32
23	P77	29.467780	-25.484170	687	2145	0.32
24	P78	29.442500	-25.613060	706	2050	0.34
25	P79	29.610830	-25.405830	679	2054	0.33
26	P80	29.629720	-25.337780	649	2122	0.31
27	P81	29.741670	-25.243330	704	2012	0.35
28	P82	28.138330	-25.039720	564	2286	0.25
29	P83	28.290280	-25.278060	579	2264	0.26
30	P84	28.400000	-25.010000	608	2245	0.27
31	P591	26.044450	-29.094170	508	2354	0.22

Figure 3.2 An example of the climate data table

To combine two or more tables using Microsoft Access (2003) the following steps were taken. In this example the original land type survey data was combined with the climate data. Originally both tables were in the Microsoft Excel (2003) format.

Step 1: the tables are transferred from Microsoft Excel (2003) to Microsoft Access (2003) by linking them as shown in Figure 3.3a and 3.3b.

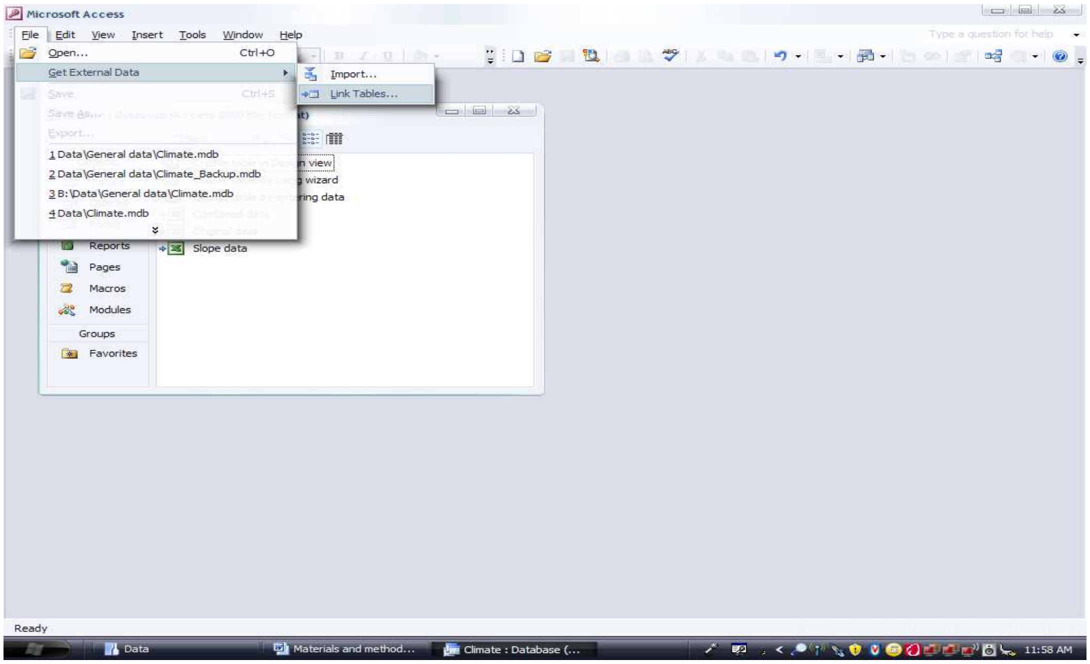


Figure 3.3a An example of importing external data in Microsoft Access (2003)

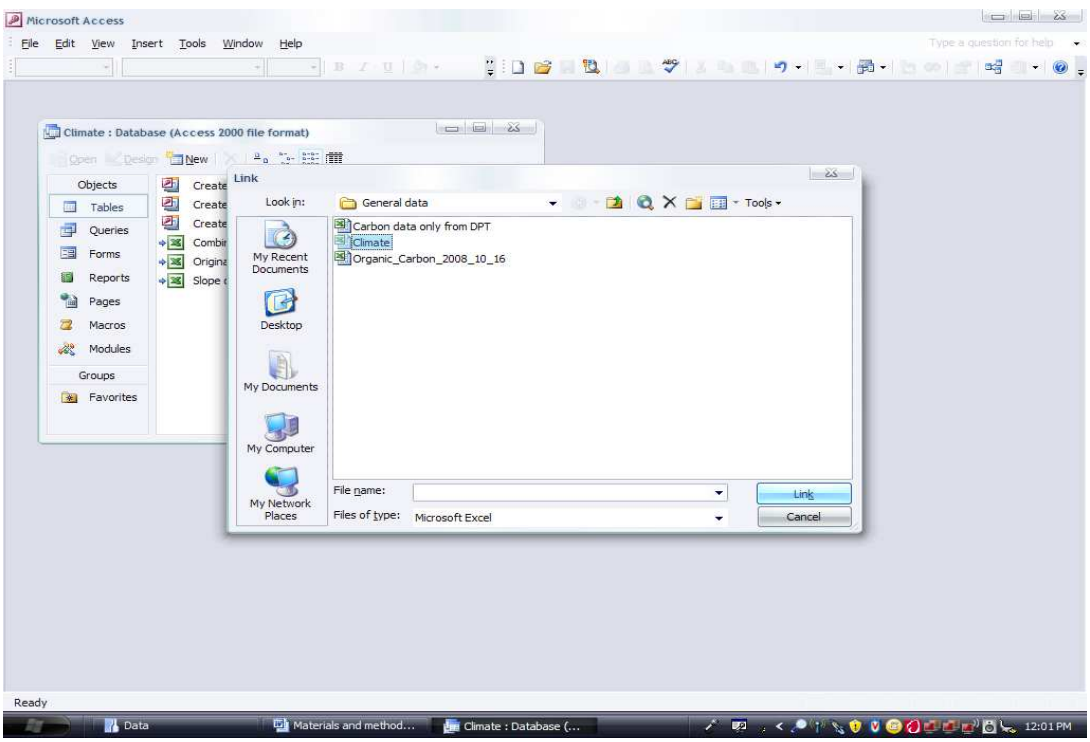


Figure 3.3b An example of linking tables in Microsoft Access (2003)

Step 2: After the two tables which contain the needed information have been added to the Microsoft Access (2003) spreadsheet, a query is created as shown in Figure 3.4a. The tables needed for the query are added and most importantly there should be a common column for identification in both tables *e.g.* profile number, master horizon *etc.* These parameters help in relating the tables. The query is run (Figure 3.4b).

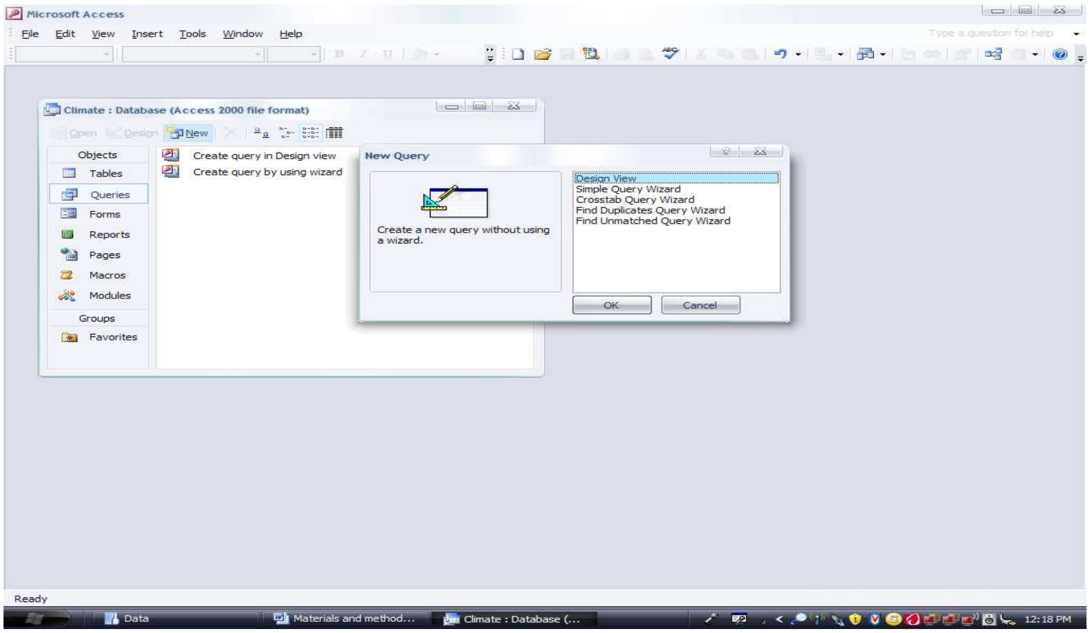


Figure 3.4a An example of creating a query

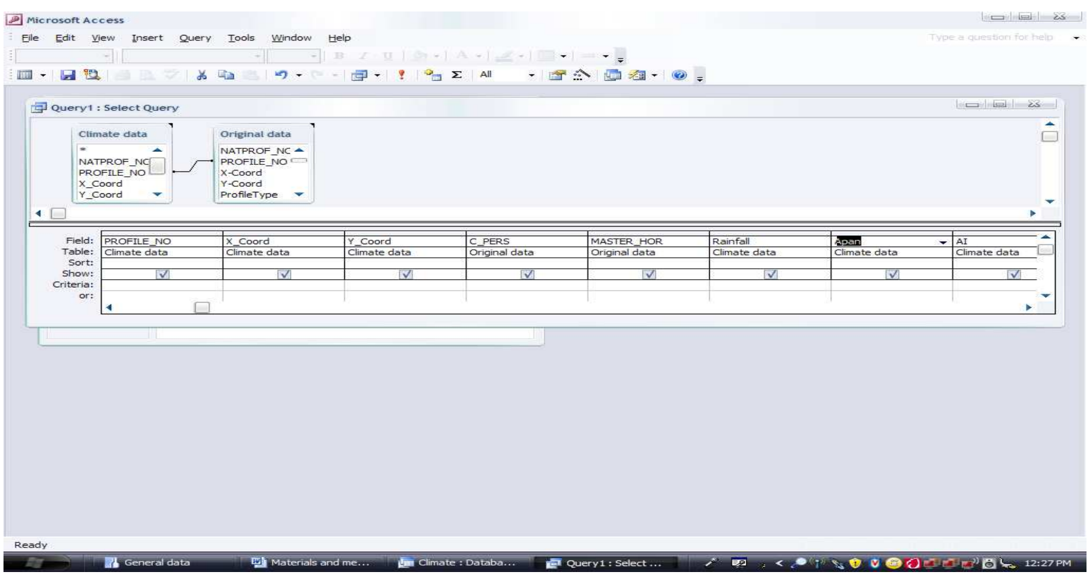
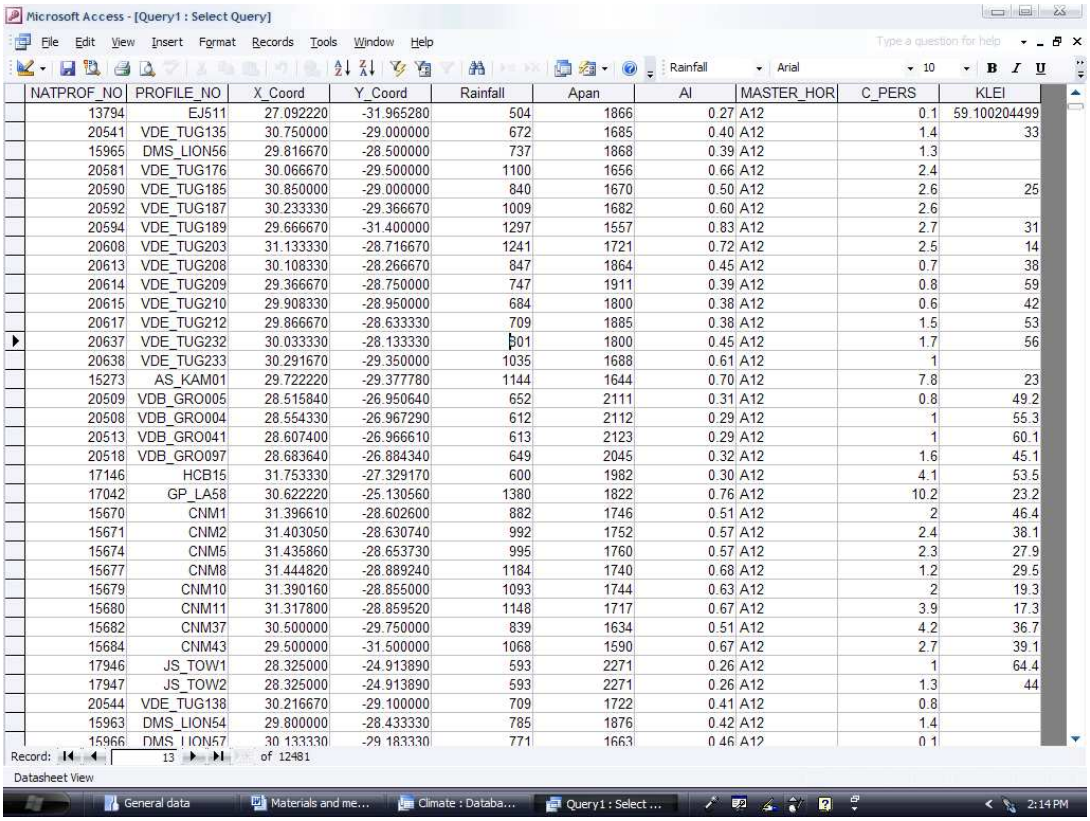


Figure 3.4b An example of running a query

Step 3: The results as shown in Figure 3.5 are a combined table which shows the original land type survey data and the climate data. This table is then transferred to the Microsoft Excel spreadsheet for the drawing of graphs.



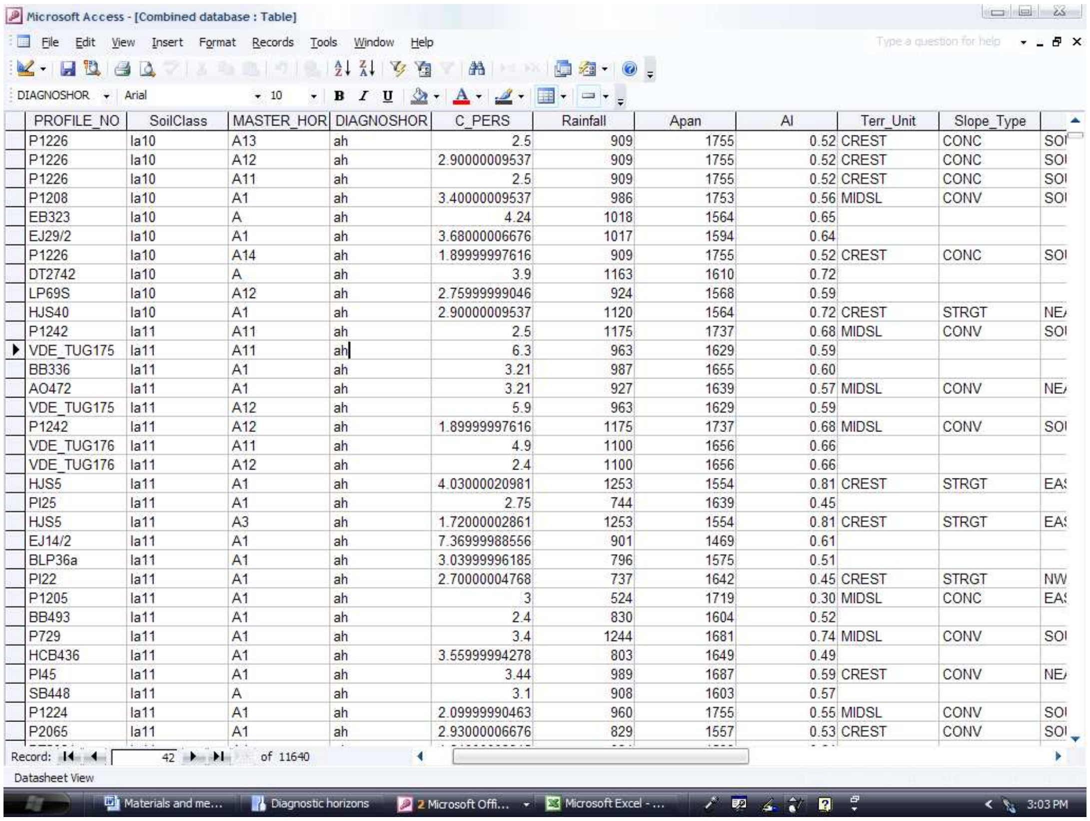
NATPROF_NO	PROFILE_NO	X_Coord	Y_Coord	Rainfall	Apan	AI	MASTER_HOR	C_PERS	KLEI
13794	EJ511	27.092220	-31.965280	504	1866	0.27	A12	0.1	59.100204499
20541	VDE_TUG135	30.750000	-29.000000	672	1685	0.40	A12	1.4	33
15965	DMS_LION56	29.816670	-28.500000	737	1868	0.39	A12	1.3	
20581	VDE_TUG176	30.066670	-29.500000	1100	1656	0.66	A12	2.4	
20590	VDE_TUG185	30.850000	-29.000000	840	1670	0.50	A12	2.6	25
20592	VDE_TUG187	30.233330	-29.366670	1009	1682	0.60	A12	2.6	
20594	VDE_TUG189	29.666670	-31.400000	1297	1557	0.83	A12	2.7	31
20608	VDE_TUG203	31.133330	-28.716670	1241	1721	0.72	A12	2.5	14
20613	VDE_TUG208	30.108330	-28.266670	847	1864	0.45	A12	0.7	38
20614	VDE_TUG209	29.366670	-28.750000	747	1911	0.39	A12	0.8	59
20615	VDE_TUG210	29.908330	-28.950000	684	1800	0.38	A12	0.6	42
20617	VDE_TUG212	29.866670	-28.633330	709	1885	0.38	A12	1.5	53
20637	VDE_TUG232	30.033330	-28.133330	801	1800	0.45	A12	1.7	56
20638	VDE_TUG233	30.291670	-29.350000	1035	1688	0.61	A12	1	
15273	AS_KAM01	29.722220	-29.377780	1144	1644	0.70	A12	7.8	23
20509	VDB_GRO005	28.515840	-26.950640	652	2111	0.31	A12	0.8	49.2
20508	VDB_GRO004	28.554330	-26.967290	612	2112	0.29	A12	1	55.3
20513	VDB_GRO041	28.607400	-26.966610	613	2123	0.29	A12	1	60.1
20518	VDB_GRO097	28.683640	-26.884340	649	2045	0.32	A12	1.6	45.1
17146	HCB15	31.753330	-27.329170	600	1982	0.30	A12	4.1	53.5
17042	GP_LA58	30.622220	-25.130560	1380	1822	0.76	A12	10.2	23.2
15670	CNM1	31.396610	-28.602600	882	1746	0.51	A12	2	46.4
15671	CNM2	31.403050	-28.630740	992	1752	0.57	A12	2.4	38.1
15674	CNM5	31.435860	-28.653730	995	1760	0.57	A12	2.3	27.9
15677	CNM8	31.444820	-28.889240	1184	1740	0.68	A12	1.2	29.5
15679	CNM10	31.390160	-28.855000	1093	1744	0.63	A12	2	19.3
15680	CNM11	31.317800	-28.859520	1148	1717	0.67	A12	3.9	17.3
15682	CNM37	30.500000	-29.750000	839	1634	0.51	A12	4.2	36.7
15684	CNM43	29.500000	-31.500000	1068	1590	0.67	A12	2.7	39.1
17946	JS_TOW1	28.325000	-24.913890	593	2271	0.26	A12	1	64.4
17947	JS_TOW2	28.325000	-24.913890	593	2271	0.26	A12	1.3	44
20544	VDE_TUG138	30.216670	-29.100000	709	1722	0.41	A12	0.8	
15963	DMS_LION54	29.800000	-28.433330	785	1876	0.42	A12	1.4	
15966	DMS_LION57	30.133330	-29.183330	771	1663	0.46	A12	0.1	

Figure 3.5 An example of a table with land type survey data and climate data

Step 5: Similar steps were followed and the terrain morphological unit, slope percentage, slope aspect and slope type data were added to the rest of the data (Figure 3.6). The results are shown in a general table containing all the parameters as listed in Table 3.3.

After the creation of applicable databases, graphs were drawn that relate organic carbon to the other parameters namely: rainfall, evaporation, aridity index, clay percentage, terrain morphological units, slope percentage, slope aspect, and slope type.

A linear regression was used to study the correlation per diagnostic horizon between the dependent variable which is organic carbon and the independent variables namely; rainfall, evaporation, slope aspect, aridity index, and clay. A stepwise regression procedure was done using the SAS statistical package (SAS Institute Inc., 2004) software. The number of samples used was different for the independent variables as the database did not include equal numbers of samples of analyses for all the particular parameters.



PROFILE_NO	SoilClass	MASTER_HOR	DIAGNOSHOR	C_PERS	Rainfall	Apan	AI	Terr_Unit	Slope_Type	
P1226	Ia10	A13	ah	2.5	909	1755	0.52	CREST	CONC	SO
P1226	Ia10	A12	ah	2.90000009537	909	1755	0.52	CREST	CONC	SO
P1226	Ia10	A11	ah	2.5	909	1755	0.52	CREST	CONC	SO
P1208	Ia10	A1	ah	3.40000009537	986	1753	0.56	MIDSL	CONV	SO
EB323	Ia10	A	ah	4.24	1018	1564	0.65			
EJ29/2	Ia10	A1	ah	3.68000006676	1017	1594	0.64			
P1226	Ia10	A14	ah	1.89999997616	909	1755	0.52	CREST	CONC	SO
DT2742	Ia10	A	ah	3.9	1163	1610	0.72			
LP69S	Ia10	A12	ah	2.75999999046	924	1568	0.59			
HJS40	Ia10	A1	ah	2.90000009537	1120	1564	0.72	CREST	STRGT	NE
P1242	Ia11	A11	ah	2.5	1175	1737	0.68	MIDSL	CONV	SO
VDE_TUG175	Ia11	A11	ah	6.3	963	1629	0.59			
BB336	Ia11	A1	ah	3.21	987	1655	0.60			
AO472	Ia11	A1	ah	3.21	927	1639	0.57	MIDSL	CONV	NE
VDE_TUG175	Ia11	A12	ah	5.9	963	1629	0.59			
P1242	Ia11	A12	ah	1.89999997616	1175	1737	0.68	MIDSL	CONV	SO
VDE_TUG176	Ia11	A11	ah	4.9	1100	1656	0.66			
VDE_TUG176	Ia11	A12	ah	2.4	1100	1656	0.66			
HJS5	Ia11	A1	ah	4.03000020981	1253	1554	0.81	CREST	STRGT	EA
PI25	Ia11	A1	ah	2.75	744	1639	0.45			
HJS5	Ia11	A3	ah	1.72000002861	1253	1554	0.81	CREST	STRGT	EA
EJ14/2	Ia11	A1	ah	7.36999988556	901	1469	0.61			
BLP36a	Ia11	A1	ah	3.03999996185	796	1575	0.51			
PI22	Ia11	A1	ah	2.70000004768	737	1642	0.45	CREST	STRGT	NW
P1205	Ia11	A1	ah	3	524	1719	0.30	MIDSL	CONC	EA
BB493	Ia11	A1	ah	2.4	830	1604	0.52			
P729	Ia11	A1	ah	3.4	1244	1681	0.74	MIDSL	CONV	SO
HCB436	Ia11	A1	ah	3.55999994278	803	1649	0.49			
PI45	Ia11	A1	ah	3.44	989	1687	0.59	CREST	CONV	NE
SB448	Ia11	A	ah	3.1	908	1603	0.57			
P1224	Ia11	A1	ah	2.09999990463	960	1755	0.55	MIDSL	CONV	SO
P2065	Ia11	A1	ah	2.93000006676	829	1557	0.53	CREST	CONV	SO

Figure 3.6 An example of a table with organic carbon, topography, and climate data

All the independent variables affect the dependent variable in a linear way and are independent of each other, therefore they resulted in a linear regression model (Equation 3.1). To test the significance of each independent variable (X) a partial F test was done especially if all the other variables were included in the model. The test was also done to determine whether the addition of a variable contributed significantly to the prediction of the dependent variable (Y).

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 \ldots \tag{3.1}$$

Where: Y = dependent variable

b_0 = Y intercept

b_1, b_2, b_3 = regression coefficients estimated from sample data

X_1, X_2, X_3 = independent variables

The stepwise regression procedure was then used for the selection of the best regression model. Each of the X-variables that was already in the model was re-tested for each new variable that was accepted. In some cases a variable that was previously accepted into the model was excluded depending on the significance of its contribution that it made to the model. If a partial F test was not significant then the variable was removed from the model. The maximum coefficient of determination (R^2) assisted in determining the contribution of a variable to the model and selecting the best model. All variables were tested at 0.15 significance level for entry into the model.

To improve the results as well as the correlation (R^2) the data was grouped initially into provinces namely: Free State, Gauteng, Eastern Cape, Western Cape, Northern Cape, Mpumalanga, KwaZulu-Natal, North West, and Northern Province. At a later stage the data focussed only on the orthic A horizon, the most common diagnostic topsoil horizon in South Africa. The data was grouped according to the subsoils and underlying materials of the orthic A as shown in Table 3.6. Regressions were then done on the data to establish the most appropriate model to estimate soil organic carbon levels in South Africa.

Table 3.6 Orthic A groups

Soil group	Subsoils and underlying materials
Apedal	Red apedal B, neocutanic B and yellow-brown apedal B
Structured	Red structured B, pedocutanic B and prismacutanic B
Lithic	Lithocutanic B and rock
Hydric	Soft plinthic B, E horizon, G horizon and hard plinthic B

CHAPTER 4

ORGANIC CARBON CONTENT IN SOIL MASTER HORIZONS OF SOUTH AFRICA

4.1 Introduction

The interaction of the factors of soil formation namely: climate, parent material, land cover and/or vegetation, and topography (Jenny, 1941) result in a variation in organic carbon content of soil. Scotney and Dijkhuis (1990) state that climate and parent material and a variety of other processes of weathering actually result in a remarkable character of South African soils. If the dynamics of soil organic carbon across the landscape are well recognized, the conservation of soil organic carbon as well as the development of models that can be used to estimate and predict soil organic carbon will be understood (Ritchie *et al.,* 2007).

The South African Taxonomical Soil Classification System (Soil Classification Working Group, 1991) makes provision for a very comprehensive relationship of properties between the diverse types of soil that are found in South Africa. It also emphasizes the importance of the identification of horizons within profiles. The universal master horizons are identified and then the different soil properties found within each horizon help the classifier to group the different soils into diagnostic horizons. Using the land type survey data (Land Type Survey Staff, 2003) the organic carbon content in the soil master horizons of South Africa was investigated. This was done by investigating the relationship between soil organic carbon and the soil forming factors namely: climate and topography as well as soil texture.

4.2 Procedure

The collection and processing of data is described thoroughly in Chapter 3. However, a concise description of the procedural dealing with the data for this chapter is given here. The land type survey data revealed that the most common master horizons are: O, A, E, B, G, C, and R horizons. Some of the master horizons were subdivided vertically and numbered *e.g.* A1, A2, B1, B2, and B3 during classification. Based on the structure of the South African Taxonomical Soil Classification System (Soil Classification Working Group, 1991), all the horizons that belong to the same master horizon but with different numbers were grouped together as shown in Table 4.1. The transition horizons were also grouped into the master horizons indicated by the first letter, with the first letter being the dominant master horizon.

Table 4.1 Grouping of master horizons, master horizon subdivisions, and transition horizons

Master horizon	Master and transition horizons
O	O, O2, O21, O22, O23, OA
A	Ap, A, A1, A11, A12, A13, A14, A3, A31, AB, AC, AE, AG
E	E, E1, E11, E12, E2, E3, E4, EG, A2, A21, A22
B	B, B1, B2, B21, B22, B23, B3, B31, B32, BC
C	C, C1, C1R, C2, C3, C4, C5
G	G, G1, G2, G3
R	R

The overburden which is a horizon that normally overlies the soil and is therefore entirely unlike the underlying material, was excluded from the dataset as it had only three data points. Based on the definition of a master horizon (Soil Classification Working Group, 1991), the overburden cannot be considered as a genetic horizon, therefore its contribution to the study was thought to be insignificant. All the data points with an organic carbon content of zero were also deleted, together with the points that have missing organic carbon data. All the organic carbon content values in the land type database are in percentages. The classification showed some errors for example, in the O horizon some data points had an organic carbon content of less than 3% which is not diagnostic of the O horizon, and therefore those points were deleted from the database to minimize the uncertainty in the data.

Some statistical analyses were done on the organic carbon contents of each of the seven master horizons listed in Table 4.1 namely: mean, standard error, 25th percentile, median, and 75th percentile. The effect of climate (rainfall, evaporation, and aridity index), topography (terrain morphological units, slope percentage, slope type, and slope aspect) and soil texture (clay content) was then investigated per master horizon. Using only the variables of climate, topography, and texture that are discreet, a model to estimate the soil organic carbon in the soil master horizons was developed by combining all the variables and doing a regression. The standard error bars were used to test significance of difference as suggested by Cumming *et al.* (2007) which showed that the overlapping of the standard error bars meant the horizons were not significantly different from each other and *vice versa.* They also state that the amount of variation in the data can be revealed by the length of the error bars.

4.3 Results and discussion

The data points of the different master horizons ranged from 6 461 points for the A horizon to 14 points for the R horizon (Table 4.2). On average the organic carbon content of the O horizon was the highest at 15.98% with a median value of 12.70%. The O horizon should have at least 10% organic carbon (Soil Classification Working Group, 1991), resulting in the fact that the 75th percentile was 19.90% organic carbon. However, the C horizon, being a mineral horizon that includes weathered rock, had the lowest organic carbon content with a 75th percentile of 0.30% and an average organic carbon content of 0.27%.

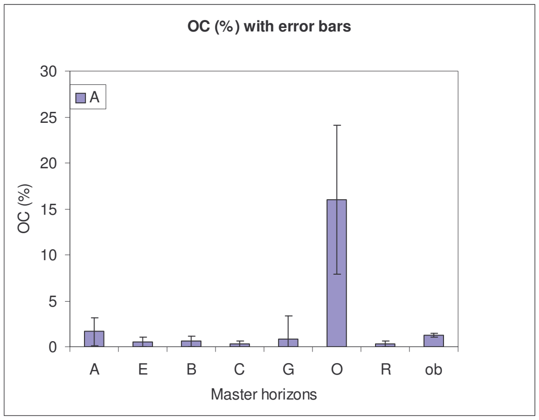
The A horizon has the second highest mean organic carbon content of 1.64% and a median value of 1.20% (Table 4.2). This horizon is normally a surface horizon that contains well-mixed humified organic matter (Soil Classification Working Group, 1991; White, 2006). Barnard (2000) found the highest organic carbon content in the A horizons in South African soils to be 1.22% which is slightly lower than what was discovered in this study.

Table 4.2 Statistical data for the master horizons

Horizons	Count (n)	Mean	Standard error	25th percentile	Median	75th percentile
A	6461	1.64	0.02	0.61	1.20	2.27
E	437	0.54	0.02	0.20	0.42	0.70
B	4026	0.59	0.01	0.21	0.40	0.70
C	651	0.27	0.01	0.10	0.20	0.30
G	97	0.80	0.26	0.20	0.40	0.60
O	12	15.98	2.33	9.98	12.70	19.90
R	14	1.29	0.07	0.10	0.15	0.40

Standard error bars were drawn per master horizon to determine the significance of organic carbon contents (Figure 4.1). The O master horizon was significantly different from all the others, because of the high organic carbon content. There was no difference in organic carbon content between the A, E, B, G, and R horizons. All these master horizons are mineral horizons excluding the R, which is made up of consolidated bedrock (Soil Classification Working Group, 1991). Surprisingly, an average of 1.29% organic carbon was found in the R, but the median value of 0.15% gives a clear indication of the low organic carbon content in this horizon. Buol *et al.* (2003) stated that the R horizon normally has small cracks that are partially or utterly filled with soil material and occupied by plant roots which may be the reason for the small amount of organic carbon that was found in this horizon.

Also, the major volume of the R horizons could have been removed by sieving as coarse fragments during soil preparation, causing a relative enrichment of soil C.



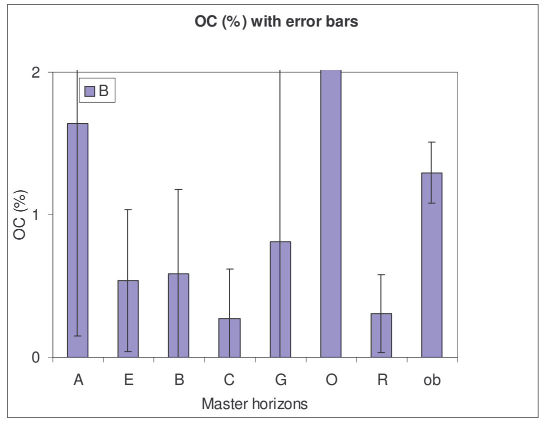


Figure 4.1 Organic carbon content with error bars in all master horizons (A) and without O horizons (B)

However, the E horizon with an average organic carbon content of 0.54% is among the horizons with a very low organic carbon content. The E horizon is characterized by the Soil Classification Working Group (1991) as a horizon with organic matter content lower than the overlying or underlying horizons. Normally it underlies A horizons and overlies B and G horizons. The results as shown in Table 4.2 confirmed the theory since the A horizons had an organic carbon mean value of 1.64% which is higher than the organic carbon content of 0.54% that was found in the E master horizons. However the underlying B (0.59% C) and G (0.80% C) horizons had a higher organic carbon content than the E horizons. The average organic carbon content of the G horizon (0.80% C) was higher than the B (0.59%), E (0.54%), and C (0.27%). This was probably because the G horizon has more moisture than the B, E, and C horizons since it undergoes prolonged periods of saturation with water except when it is drained (Soil Classification Working group, 1991). The activity of microorganisms is controlled by the moisture content of the soil and it slows down under high moisture contents which result in less soil organic matter decomposition (Havlin *et al.,* 1999).

4.3.1 Climate

Climate as a soil forming factor controls the amount of organic carbon found in the soil by affecting the rate at which plant litter is produced and decomposed (Hontoria *et al.*, 1999). The relationship between the most important climate components namely rainfall, evaporation, and aridity index was explored per master horizon. The climate data for the different modal profiles was extracted from the climatic records compiled by Schulze (2006).

Stray data points or outliers were found in the A, E, C, and G horizons. These points were not included when determining the correlation coefficient (R^2). This decision was done based on the belief that there might have been an error during classification or analysis. Some of the points may have been from samples that were taken from calcareous soils and because the carbon from the lime may not have been removed before chemical analysis and this may have a great impact on the results.

4.3.1.1 O horizon

The O horizons had the highest amount of organic carbon content of 32.6% amongst the master horizons. According to Figure 4.2 the best correlation found in this horizon was between evaporation and organic carbon (R^2 = 0.40). Even though this is an organic horizon with the accumulation of organic material under wet conditions (Soil Classification Working Group, 1991; White, 2006) there was no correlation with rainfall.

Areas with the highest rainfall had a lower amount of organic carbon *e.g.* a rainfall of 1639 mm gave an organic carbon content of 13.3% whilst a rainfall of 689 mm gave an organic carbon content of 32.6%. The difference may be accounted for by the positions of the soils in the landscape which causes a lot of variation in temperature and precipitation of the areas by affecting the microclimate of the area (White, 2006). Sims and Nielsen (1986) stated that, in general, precipitation increases with altitude resulting in more vegetation production. They also stated that as the altitude increases the temperature decreases which lead to less microbial activity, therefore resulting in the accumulation of soil organic carbon. The O horizons were found in areas with a rainfall of 369 mm to 1639 mm, evaporation of between 1510 mm and 2176 mm and an average aridity index of 0.52. This proves that this master horizon is formed in the humid parts of South Africa while it also occurs in subhumid areas where there is high biomass production and pronounced long duration wetness in lowland positions.

Rainfall and aridity index had a negative impact on the organic carbon content of the O horizon (Figure 4.2). Even though the correlation was very low, organic carbon decreased with an increase in rainfall and aridity index. However, it was expected that organic carbon content would increase with an increase in rainfall in the O horizon as they would be saturated for longer periods of time, therefore promoting accumulation of organic carbon (White, 2006). More soil moisture also leads to deeper O horizons (White, 2006).

Surprisingly, evaporation affected organic carbon content positively in the O horizons. The Soil Classification Working Group (1991) stated that the O horizon can also be formed under non-saturated conditions. As the moisture content in these horizons decreases due to evaporation the organic carbon decomposition was expected to increase since the conditions become conducive for microbial action. This is because lower soil moisture content promotes aerobic conditions needed for microbial activity (Havlin *et al.,* 1999). However the effect of increased temperatures associated with evaporation (Tate, 1992a) probably resulted in more plant litter production. Increased plant material either above or below-ground contributes positively to organic C levels (White, 2006). Therefore evaporation affected the level of organic carbon in these horizons positively. The highest evaporation rate of 2176 mm was associated with an organic carbon content of 32.6% which was very high probably due to increased organic material because of warmer temperatures.

4.3.1.2 A horizon

The relationship between soil organic carbon and climate in the A master horizons is illustrated in Figure 4.3. In general there was a poor correlation between organic carbon and rainfall, evaporation, and aridity index. However, the highest correlation was found between organic carbon and aridity index (R^2 = 0.32), followed by rainfall (R^2 = 0.28), and lastly evaporation (R^2 = 0.22). Unfortunately, the data failed to give a clear picture of which variable could be highly associated with soil organic carbon in the A horizon.

The A horizon being the most common master horizon in South Africa, occurs in areas with a rainfall ranging from 21 mm to 1639 mm and evaporation of 1237 mm to 3029 mm. The average aridity index was 0.39. There was a linear relationship between organic carbon and rainfall and aridity index, whereas it was inversely correlated with evaporation in the A horizon.

Several scientists have investigated the correlation between organic carbon and the factors of climate. Alvarez and Lavado (1998) and Dai and Huang (2006) reported that there was a positive correlation between soil organic matter content and mean annual precipitation. Hontoria *et al.* (1999) and Jobbagy and Jackson (2000) also reported that soil organic carbon was best correlated with mean annual precipitation. Alvarez and Lavado (1998) stated that as organic carbon increased with precipitation it also decreased with higher temperature. Sims and Nielsen (1986) also found that organic carbon content was better predicted by mean annual precipitation and elevation. Low temperature and high rainfall promote accumulation of soil organic matter, while low rainfall and high temperature cause a decrease in soil organic matter content (Smith & Elliott, 1990).

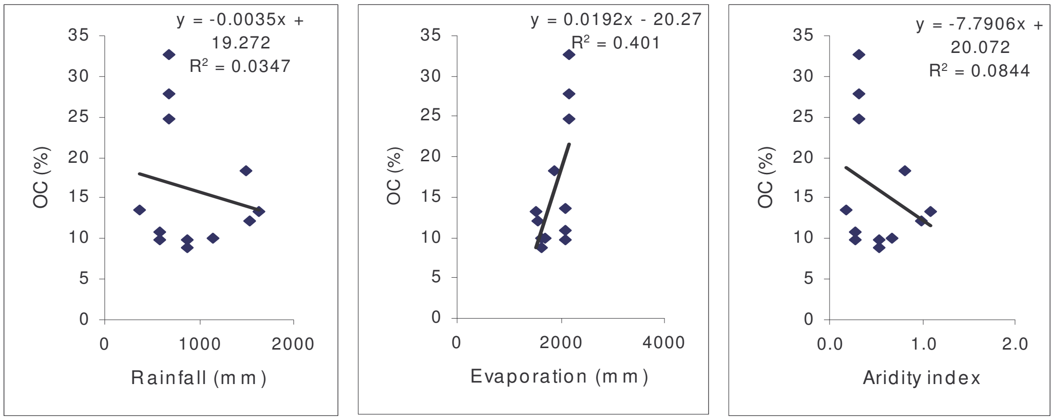


Figure 4.2 Relationship between organic carbon and elements of climate in the O horizon

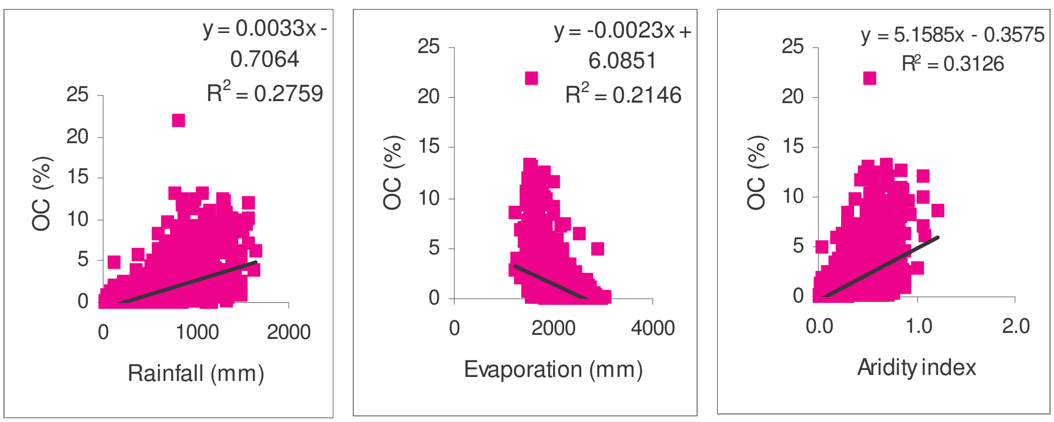


Figure 4.3 Soil organic carbon relationship with climate factors in the A horizon

4.3.1.3 E horizon

There is a very poor relationship between organic carbon and rainfall (R^2 = 0.09), evaporation (R^2 = 0.11), and aridity index (R^2 = 0.11) in the E horizon (Figure 4.4). The E horizon has usually undergone eluviation (Soil Classification Working Group, 1991; Le Roux *et al.,* 1999; White, 2006) therefore is characterised by low levels of organic carbon with an average of 0.54%. The evaporation in areas where these horizons are found ranged between 1480 mm to 2595 mm with rainfall ranging between 89 mm to 1567 mm. The average aridity index where this horizon occurs is 0.40 which is reasonably low. Evaporation was inversely proportional to organic carbon in the E horizon. The relationship between organic carbon and rainfall and aridity index was positive.

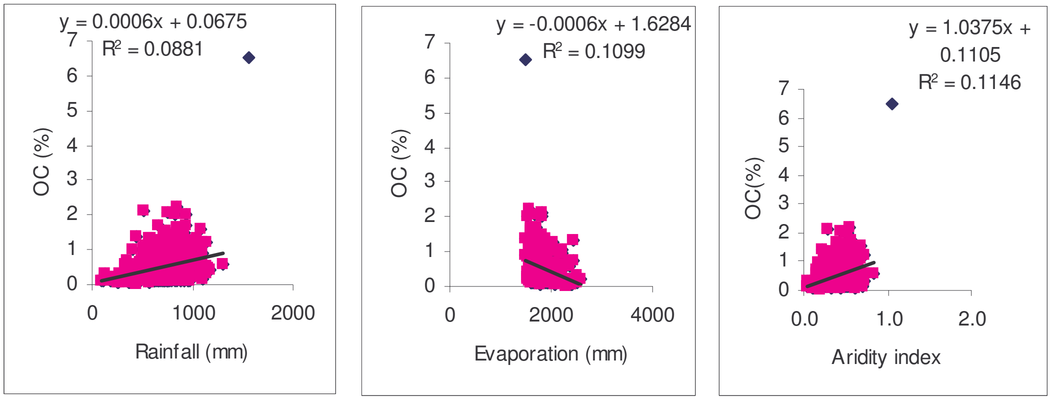


Figure 4.4 Relationship between organic carbon and elements of climate in the E horizon

4.3.1.4 B horizon

There was a very low correlation between soil organic carbon content and rainfall (R^2 = 0.13), evaporation (R^2 = 0.12) and aridity index (R^2 = 0.15) in the B horizon as illustrated in Figure 4.5. The rainfall for this horizon is between 27 mm and 1628 mm while evaporation ranged from 1237 mm to 3029 mm. The B horizons were found within a wide range of climatic conditions with the aridity index ranging from between 0.01 which is arid to 1.06 which is humid. None of the elements of climate can be used to estimate the amount of soil organic carbon in the B horizons because of the low correlation coefficients.

4.3.1.5 G horizon

There was also a very low correlation between organic carbon and rainfall (R^2 = 0.09), evaporation (R^2 = 0.06) and aridity index (R^2 = 0.12) in the G horizon (Figure 4.6). Compared to rainfall and evaporation, the correlation between aridity index and organic carbon was a little bit better but it was still too low to draw conclusions from. From Figure 4.6 it is clear that the G horizon is found in semi-arid areas with an average aridity index of 0.40 and in subhumid and humid areas with rainfall of 65 mm to 1208 mm and evaporation of 1565 mm to 2915 mm.

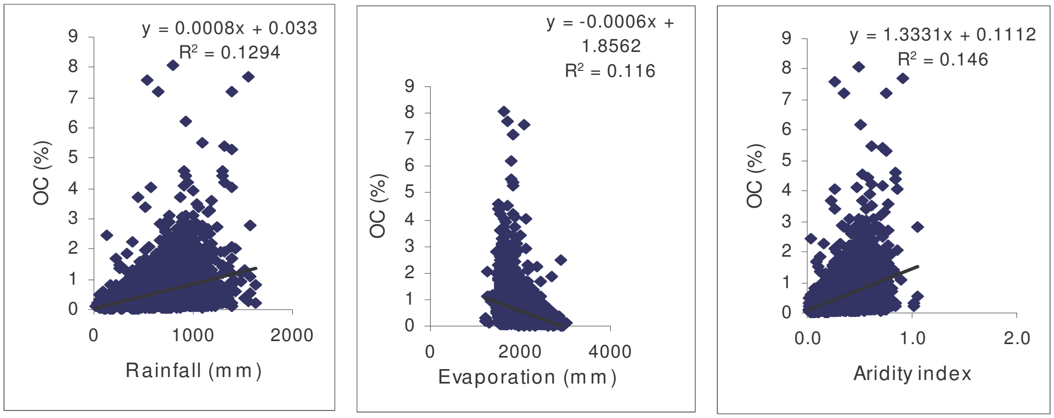


Figure 4.5 Relationship between organic carbon and elements of climate in the B horizon

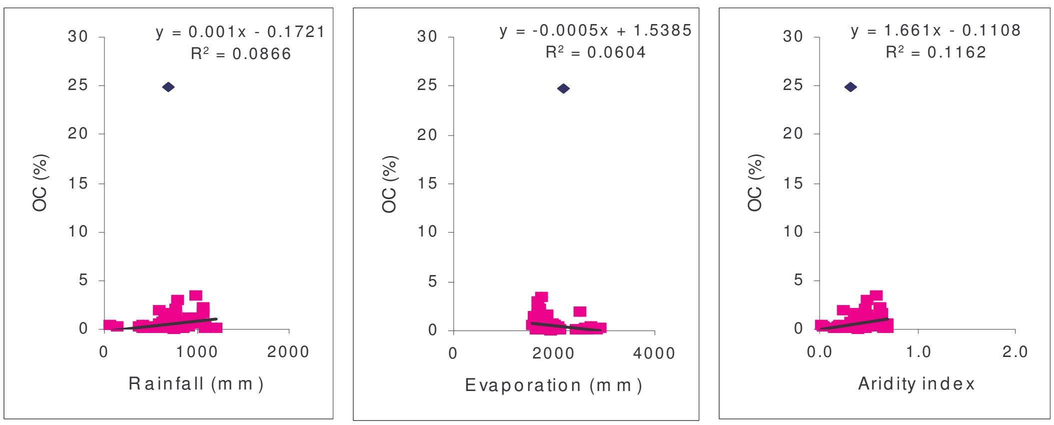


Figure 4.6 Relationship between organic carbon and elements of climate in the G horizon

4.3.1.6 C horizon

The C horizons are usually found below the B horizon are often referred to as the "parent material" horizon (Courtney & Trudgill, 1984). Unfortunately there was no connection between organic carbon and the elements of climate in the C horizons. This may probably be because of its position in the profile which is usually way below the lowest B horizon (Soil Classification Working Group, 1991). The position might be too deep for the factors of climate to affect the levels of organic carbon in this horizon. Oades (1995) also stated that soil organic carbon content normally declines with depth. The C horizons were found in areas with rainfall of between 21 mm to 1547 mm and evaporation of 1262 mm to 2915 mm. The relationship between organic carbon and evaporation was found to be negative while it was positive with rainfall and aridity index (Figure 4.7).

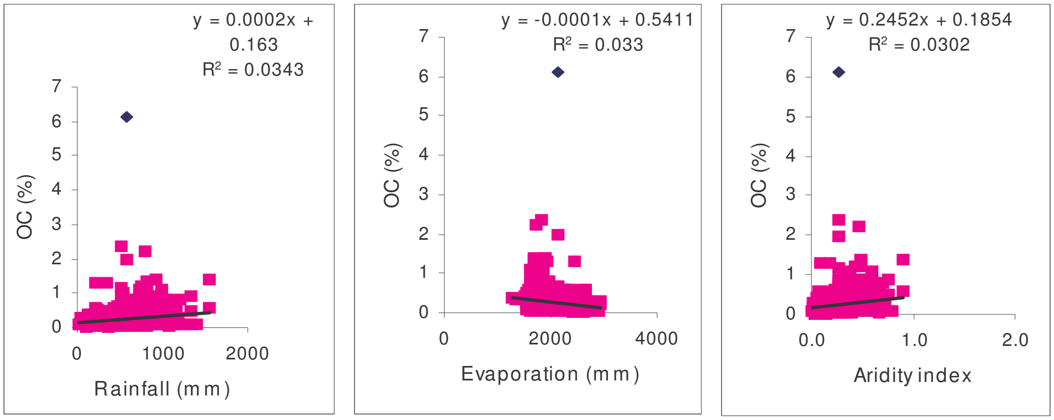


Figure 4.7 Relationship between organic carbon and elements of climate in the C horizon

4.3.1.7 R horizon

The R horizon which is basically made up of bedrock had a very low amount of organic carbon. This horizon yielded better correlation coefficient (R^2) values than the other master horizons (Figure 4.8). The highest was for evaporation at R^2 = 0.45, followed by the aridity index at R^2 = 0.38, and rainfall at R^2 = 0.36. Although these values were higher than in other master horizons they were still not significant enough to model the relationship between organic carbon and the components of climate in the R horizon. There was a linear relationship between organic carbon, rainfall, and aridity index. Evaporation was inversely proportional to organic carbon in the hard rock horizon. The hard rocks were found in very dry areas with a rainfall of 56 mm to 651 mm and evaporation of 2124 mm and 2778 mm. The average aridity index where these horizons were found was 0.09. Fey (2009) stated that soils with hard rock are mostly found in dry areas because of less chemical weathering.

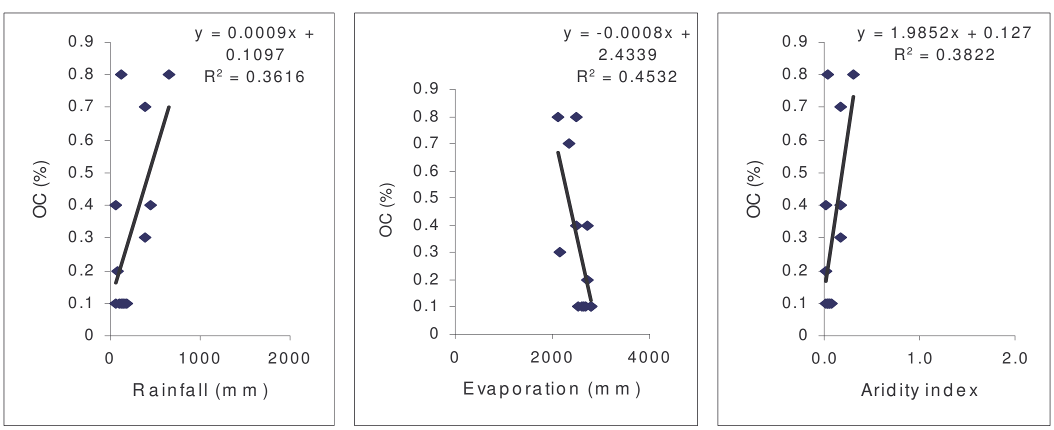


Figure 4.8 Relationship between organic carbon and elements of climate in the R horizon

There was a poor correlation (R^2) between organic carbon content and rainfall, evaporation and aridity index in all the master horizons. Organic carbon content was positively correlated with rainfall and aridity index in the A, E, B, G, C, and R master horizons whereas it was inversely correlated with evaporation in those horizons. The O horizons behaved in a different manner from the other horizons. The relationship between organic carbon and evaporation was positive in the O horizon which is the horizon with the highest organic carbon content. Evaporation is normally related to temperature therefore if temperature increases under constant precipitation this results in decreased moisture content in that area (Tate, 1992a). Organic carbon probably increased in the O horizon as evaporation increased because an increase in evaporation means an increase in temperature which leads to increased plant production, provided the soils have enough water. This will result in more biomass production and therefore more organic material accumulates leading to increased organic carbon content in the O horizons. Temperature becomes very important in this regard since the accumulation of organic material can occur only up to a certain level, since the rate at which organic material is broken down by microbial activity, which increases with an increase in evaporation and temperature (FitzPatrick, 1983). FitzPatrick (1983) stated further that for every 10ºC increase in soil temperature the rate of the chemical reactions increases by a factor of two to three. This is probably also the reason why evaporation and organic carbon were negatively related in the A, E, B, G, C, and R master horizons because, they were probably found in areas with higher temperatures than the O horizons. The higher temperatures promote increased organic matter decomposition (FitzPatrick, 1983). Alvarez and Lavado (1998) also state that an increase in temperature causes a decrease in soil organic carbon. Therefore temperature should be included when exploring the effect of climate on the organic carbon content of the soil. From the data soil organic carbon content increases with precipitation and decreases with temperature in the A, E, B, G, C, and R master horizons. These results correlate with the findings of Kirschbaum (1995) as well as Jobbagy and Jackson (2000).

4.3.2 Topography

The influence of topography as a soil forming factor on soil organic carbon is through its components namely slope and aspect (Chapter 2). Topography affects the amount of surface runoff, erosion, and deposition and it also has a great influence by controlling drainage (White, 2006). Topography embraces slope percentage, slope aspect, the shape of slope, and terrain morphology (Le Roux *et al.,* 1999). According to Rezaei and Gilkes (2005) the landscape features that have a great impact on the organic carbon content of the soil include slope, elevation and aspect as well as land use. All these landscape features affect microbial activity, natural drainage of the area, the rate of water runoff and run-on processes as well as the vulnerability of the soil to wind and precipitation (Buol *et al.,* 1989). The physical characteristics of topography that were investigated in this study were the terrain morphology, slope percentage, slope aspect, and the shape of the slope. The correlation between these components of topography and soil organic carbon was investigated per master horizon and the results presented in the form of bar charts (Figure 4.9). The standard error bars were included to illustrate the degree of variation between the points as well as the significant differences between the means (Cumming *et al*., 2007).

4.3.2.1 Terrain morphological units

There are five terrain morphological units namely the crest, scarp, midslope, footslope, and the valley bottom (Le Roux *et al.,* 1999). The footslopes and the midslopes were further divided into the upper and lower slopes. Terrain morphology data was taken from the land type survey data and was used as it was described in the field. Organic carbon contents were grouped per terrain unit and are presented in Figure 4.9.

4.3.2.1.1 O horizon

The O horizon was found only in: foot slopes and valley bottom (Figure 4.9). The highest average organic carbon content was found at the valley bottom positions (28.4%). The footslope had an organic carbon content of 18.3%. Significance between the two could not be tested because only one point was found in the footslopes therefore no standard error could be calculated.

The O horizon is a surface organic horizon that is formed when organic material accumulates under saturated or non-saturated conditions (Soil Classification Working Group, 1991; White, 2006). This validates the formation of O horizons at the valley bottom where hydromorphic soils are found and alluvial conditions dominate and drainage is very poor. Soils found at the valley bottom are normally dark and peaty showing a high amount of organic carbon. The soils at the footslopes are poorly drained and the water table is not very deep, which allows for the slow decomposition of organic matter due to periods of saturation (White, 2006). Unfortunately there is no vast data on the O horizons, probably because these organic horizons are not widely spread in South Africa and therefore have not been sufficiently studied (Soil Classification Working Group, 1991).

4.3.2.1.2 A horizon

The A horizons were found under different terrain morphological units namely pan, footslope, scarp, lower foot slope, upper foot slope, valley bottom, midslope, crest, lower midslope, and the upper middle slope (Figure 4.9). On average organic carbon content increased from the pan (0.49%) to the upper midslope (2.14%). The average organic carbon content on the crest, where soils are formed under residual conditions, was 1.49%. The difference in organic carbon content between the crest and midslope is only 0.04% which is not significant. The A horizons in the scarps, which are usually steep, had an average organic carbon of 0.88% which is significantly lower than in the crests, probably due to a higher degree of physical weathering in the scarps. The midslope was divided into the upper and the lower midslopes. The upper midslopes had a higher average organic carbon content (2.14%) than the lower midslopes (1.49%) probably due to the settlement of the material from the upper slopes after weathering and erosion. The standard error bars also show that the difference between them is significant.

Surprisingly, the lowest average organic carbon content was found in the pan at 0.49%. This may probably be because only three observations of the A horizon in the pan were found. It may also be because salt pans are normally found in dry low lying areas where the water table may rise and bring along the dissolved salts to the surface thus leaving behind some salt residue after evaporation (FitzPatrick, 1983; White, 2006). This leads to poor vegetative production in those areas and less organic material since not all plants are salt tolerant (White, 2006). Salts tend to restrict the ability of the plants to withdraw water from soil thus affecting their growth (Warrence *et al*., 2002). A pan is a depression (Ritchie *et al.,* 2007) and can be a sign of shallow soils. The amount of organic material produced in a pan might not be enough to contribute significantly to improving soil organic matter content. As a result this is justification for the small amount of organic carbon found in the master A horizons in pans.

The A horizons that were found in the valley bottoms which usually consist of hydromorphic soils, had an average organic carbon content of 1.08% which was significantly higher than in the scarps or footslopes. Soils found in the valley bottom were expected to have a high content of organic carbon because of alluvial conditions found in this unit as well as the high water content which negatively affects the conditions for organic matter decomposition (Le Roux *et al.,* 1999).

Footslope was also divided into footslope, lower footslope, and upper footslope. Their average organic carbon content was 0.70%, 0.89%, and 0.92% respectively. The organic carbon content on the upper footslopes was not expected to be higher than in the lower footslopes. This was not anticipated because the decrease in slope which is positively correlated to organic carbon content and also because deposition in the lower areas results in more organic carbon (Ritchie *et al.,* 2007). On the contrary, the organic carbon content on the upper footslopes was probably higher than on the lower footslopes because of more vegetation on the upper footslopes which contributed more organic material than in the lower footslopes. Changes in vegetation including type and amount of vegetation control soil organic carbon storage (Angers & Carter, 1996). The organic carbon content in the footslopes (0.70%) was expected to be higher than in the scarp (0.88%). This is because soils in the footslope generally have higher organic matter contents as well as thicker A horizons (McSweeney & Grunwald, 1998). The water table is also higher on the footslopes than on the scarps resulting in more soil moisture and slower decomposition of soil organic matter (White, 2006). The error bars show that differences in organic carbon content between footslopes, upper footslopes, and lower footslopes are not significant.

4.3.2.1.3 E horizon

The E horizon is an eluvial mineral horizon that has a low organic matter content (Soil Classification Working Group, 1991). This horizon was found in the valley bottom, footslope, midslope, and crest (Figure 4.9). There were no E horizons in the scarp which was not unusual because Le Roux *et al.* (1999) states that the E horizons often occur on the transition to the scarp. The average organic carbon content increased from the upper footslope (0.28%) to the upper midslope (0.93%).

The average organic carbon content of the E horizons in the valley bottom was 0.34% which is low, but not significantly different from the organic carbon content in the upper footslopes (0.28%) and the footslopes (0.36%). Soils at the valley bottom have a higher organic carbon content than soils on the upper footslopes (Ritchie *et al.,* 2007) so the E horizons in the valley bottom were expected to have more organic carbon than at the upper footslopes and footslopes.

The E horizons in the upper footslopes had a significantly lower organic carbon content when compared to the lower footslopes. However, this was not significantly different from the footslopes. Lower footslopes (0.43%) apparently had a higher organic carbon content due to a decrease in the eluviation of materials such as organic matter that occurs in the E horizon as the water table rises and drainage becomes poorer. The water table rises as the slope decreases which means that soils at the lower footslopes are less drained when compared to soils at the upper footslopes (White, 2006).

The E horizons in the crests had an average organic carbon content of 0.54%, which was not significantly different from the organic carbon content in the midslopes and the lower midslopes. Soils that are found in the midslopes are deep and well-drained (Le Roux *et al.,* 1999) which are favourable for the removal conditions common in E horizons. The presence of a B horizon which is less permeable below the E horizon may have resulted in the preservation of an organic carbon content of 0.93% in the lower midslope which was the highest for the E horizons in South Africa. During eluviation in the E horizons organic material is usually lost laterally and to the underlying horizons (White, 2006). Therefore, the presence of a less permeable underlying horizon might contribute positively to the retention of some nutrients in the E horizons.

4.3.2.1.4 B horizon

The B horizon was found under different terrain morphological units namely: pan, valley bottom, footslope, upper and lower footslope, upper and lower midslope, scarp and the crest. Average organic carbon content ranged from 0.29% in the pan to 1.10% in the scarp (Figure 4.9). The low organic carbon content found in the B horizons at the pan was expected due to the saline conditions that are found in that area, therefore affecting vegetative growth negatively leading to less addition of organic material (Havlin *et al.,* 1999; White, 2006).

The standard error bars shown in Figure 4.9 demonstrate that the organic carbon content found in the B horizons in the pan was significantly lower than in all the other morphological units. The difference in organic carbon content between the valley bottom (0.44%) and the crest (0.58%) was not significant. Soils found at the crests are residual and those at the valley bottom are alluvial (Le Roux *et al.,* 1999). This shows that the deposition of soil from the upper slopes in the valley bottom did not contribute significantly to increased organic carbon content when compared to the soils that were left behind in the crests. The contribution of the deposited material to organic carbon levels also depends on the richness of the material in terms of nutrients (Moges & Holden, 2008).

The organic carbon content in the lower footslopes was significantly lower than the organic carbon content in the footslopes and upper footslopes. The upper midslopes also had a significantly higher organic carbon content than the lower midslopes and the midslopes. This is probably because the upper midslope is the first to receive solids and solutes *e.g.* organic carbon from the sites immediately up-slope and the rate of erosion is not as high as in the midslope and lower midslope. The rate and effect of soil erosion increased with an increase in slope gradient (FitzPatrick, 1983).

The highest average organic carbon content in B horizons was found in the scarps. Soils in the scarps are usually shallow due to the steepness (Le Roux *et al.,* 1999) with low organic carbon content but surprisingly according to Figure 4.9 they had the highest organic carbon content of 1.10%. The organic carbon content of the B horizons on the scarps was significantly higher than in the B horizons found on all the other parts of the landscape. Due to the steepness of the scarps erosion is very high and the amount of soil organic carbon in the B horizons in these slopes was expected to be low. Ritchie *et al.* (2007) found that soil organic carbon decreases with an increase in the gradient of the slope. FitzPatrick (1983) also adds that soils on steep mountain slopes are shallow, thin and prone to soil erosion. So it was expected that soil organic carbon would have been washed away with the soil during erosion but on the contrary the results showed that the B horizons at the scarps managed to retain the highest amount of soil organic carbon. However, FitzPatrick (1983) states that the availability of thick vegetation cover can result in the soils accumulating on the steep slopes thereby trapping the carbon rich soils from higher slopes and also preventing soil loss in those slopes.

4.3.2.1.5 G horizon

The G horizon was found in the midslopes, pan, footslopes, upper footslopes and at the valley bottom (Figure 4.9). On average organic carbon content ranged from 0.32% at the midslopes to 1.50% at the valley bottom. The valley bottom is normally an area where poorly drained soils are found thereby providing suitable conditions for G horizon formation (Soil Classification Working Group, 1991). Anaerobic conditions at the valley bottom are a result of a raised water table causing poor drainage. As a result microbial action is reduced and organic carbon is preserved. Anaerobic conditions such as waterlogging tend to inhibit the decomposition of soil organic matter (Carter, 1996). The highest number of observations was made at the valley bottom (n = 32). Only one observation was found at the pan. A salt pan is a result of waterlogging caused by a raised water table (White, 2006) and the high moisture conditions are conducive for the formation of a G horizon. The amount of organic carbon in G horizons found on the footslopes (0.44%) and the upper footslopes (0.51%) was not significantly different.

4.3.2.1.6 C horizon

The average organic carbon content of the master C horizons which is a mineral horizon made up of weathering parent material (Soil Classification Working Group, 1991; White, 2006), ranged from 0.16% in the lower footslope to 0.60% in the scarp (Figure 4.9). Regardless of the terrain morphological unit the organic carbon content in the C horizons remained low and within the same range. The depth and position in the profile of the C master horizon, as well as the degree of weathering and type of material of which it is made, contribute highly to the low amount of organic carbon found. Oades (1995) stated that the organic carbon content of the soil decreases with depth, so the low organic carbon contents might be because the C horizon is normally situated deeper in the profile. The absence of standard error bars in the upper footslope and the scarp was because only one sample was found of the C horizon for each of the units.

On average organic carbon content of C horizons in the lower footslope, pan, upper midslope, and lower midslope was not significantly different. The C horizon has been characterized by a very low amount of organic carbon with the valley bottom having only 0.24% which is not significantly different from the crest (0.24%). The difference between the midslope (0.28%) and the footslope (0.27%) was also not significant.

4.3.2.1.7 R horizon

The highest organic carbon content (Figure 4.9) was recorded on the crests (0.57%) and the lowest on the valley bottom (0.10%). Crests had the highest organic carbon content, because residual soils are formed on plateaus and they tend to remain in place therefore maintain reasonable organic carbon levels (FitzPatrick, 1983; Le Roux *et al.,* 1999). Hard rock is also very resistant to water and root penetration (Soil classification Working Group, 1991) that is probably why a high organic carbon content was preserved on the crests and could not be leached or eroded. Most of the observations were from the midslope (n = 7; 0.19% C), where surface erosion is high, most likely leaving the hard rock. The risk of soil erosion tends to increase with an increase in slope gradient and the upland soils are more vulnerable which is why most of the rocks were found on the midslopes (FitzPatrick, 1983; Ritchie *et al.,* 2007).

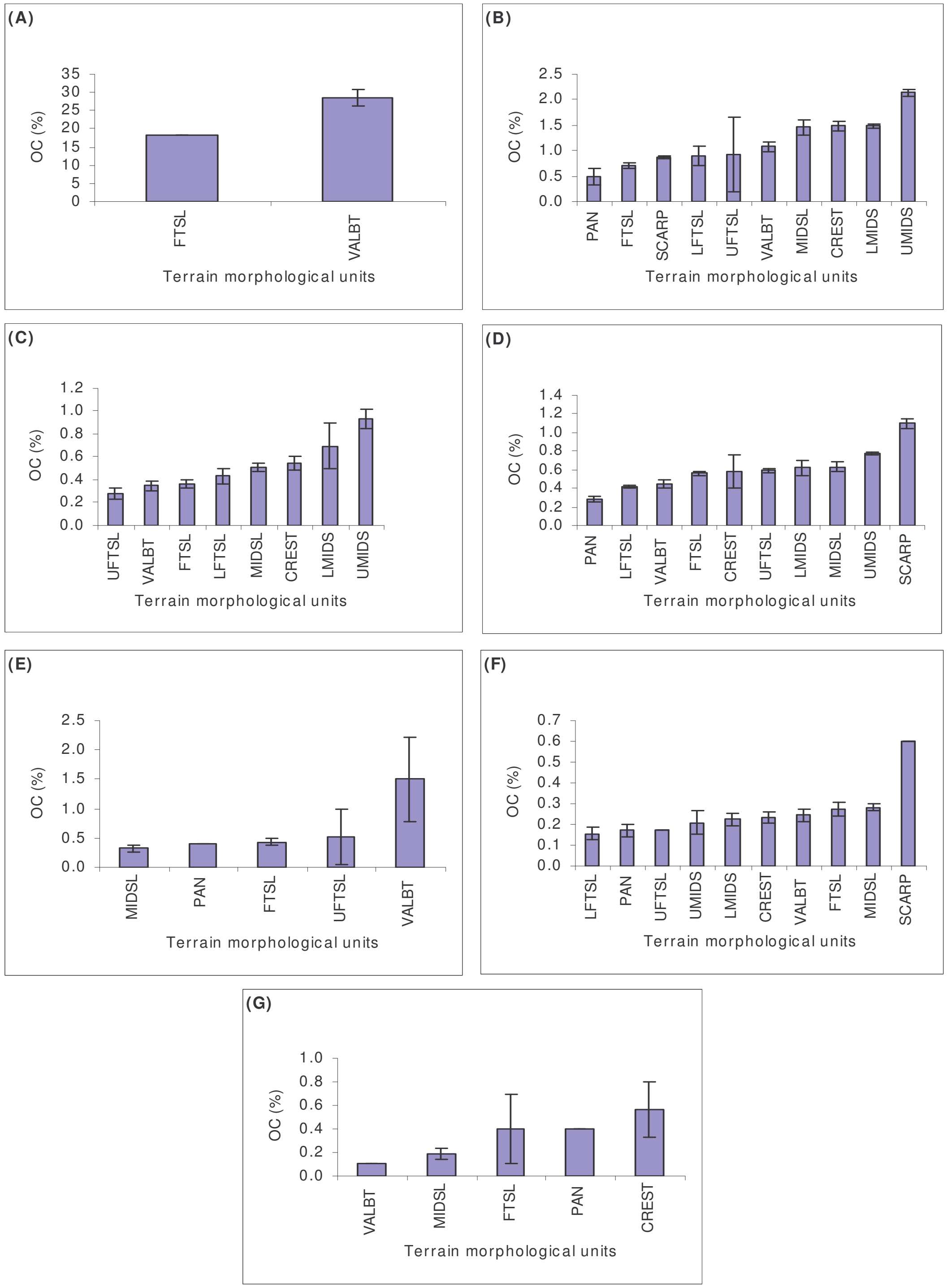


Figure 4.9 Effect of terrain morphology on organic carbon content in the soil master horizons: O horizon (A), A horizon (B), E horizon (C), B horizon (D), G horizon (E), C horizon (F), and R horizon (G)

Terrain morphological units showed a great influence on the amount of organic carbon in the master horizons in South Africa. Different master horizons were found at the pan namely: A, B, G, C, and the R. The organic carbon content ranged from 0.17% in the C horizon to 0.49% in the A horizon. The A horizon is a surface horizon where there is some accumulation of organic matter which is why it has higher amount of organic carbon.

The organic carbon of the soils on the crests ranged from 0.24% in the C horizon to 1.49% in the A horizon. Despite the elevated degree of weathering at the crests the A horizon maintained a high organic carbon content.

The soils found on the scarps are usually leached and shallow, but soils with A, B and C horizons were still found. The A horizons at the scarps had an average organic carbon of 0.88%; B had 1.10% whilst the C horizon had 0.60%. All three master horizons had a reasonable amount of organic carbon with the B having the highest. This may be because of the B horizon is an illuvial horizon, allowing for the accumulation of organic carbon.

All the common master horizons were found on the midslopes except the O horizon. The midslopes were further divided into the lower and upper midslope. The highest organic carbon contents in the A and E horizons were found in the upper midslopes. Moges & Holden (2008) also reported that the organic carbon content of soils on the lower midslopes was significantly lower than on the upper midslopes. They believe that this happened because of leaching and deposition of the coarse sediments from the upper slopes thus affecting the area and altering the soil properties. Soils in midslopes are normally well-drained with a deep water table and those conditions are compatible with the formation of the A and E horizons and not the O horizon. Surprisingly soils with G horizons were found at the midslopes even though they had low organic carbon contents.

All master horizons were found on the footslopes but had varying organic carbon contents. The amount of organic carbon found on the footslopes was moderate with respect to the different horizons, probably because soils at the footslopes are less prone to soil erosion and begin to have signs of wetness that contribute positively towards the accumulation of organic carbon. The increase in water content causes a negative impact on the activities of microbes which require aerobic conditions for the decomposition and mineralization of organic matter. Soil organic carbon is therefore preserved.

The highest organic carbon content was expected to be found at the valley bottom where the O and G horizons occur. This is because the wettest soils are found on the valley bottom where alluvium is deposited. The organic carbon content was also higher at the lower slope positions (valley bottom) because of greater water availability due to subsurface water flow, leading to higher organic matter accumulation rates. Greater water availability results in higher biomass production and higher conservation of organic material due to less microbial activity.

Topography affects the amount of organic carbon in the soil by influencing the rate of surface runoff and soil erosion which usually occurs on the midslopes and valley bottoms. Soil master horizons with the highest average organic carbon content were found at the foot slopes and the valley bottoms, where drainage is poor with a water table situated near or at the soil surface (White, 2006). These conditions are favorable for the accumulation of soil organic carbon by hindering microbial activity as well as loss of nutrients by processes such as eluviation and leaching.

4.3.2.2 Slope percentage

Slope percentage is correlated to some soil forming processes such as hydromorphism, because it affects the soil moisture regime (Le Roux *et al.,* 1999). The dynamics involved with the factors of climate, temperature, and precipitation, which also occur along the altitude gradient, control the type of vegetation found in an area as well as the quantity, rate of turnover, and the composition of soil organic matter (Hontoria *et al.,* 1999). Therefore the relationship between elevation, altitude or slope percentage is vital for understanding the changes in soil organic carbon in the landscape. Sims and Nielsen (1986) reported that soil organic carbon and altitude are positively related. Slope percentage also affects the formation of certain soils. Le Roux *et al.* (1999) stated that some soils are restricted to some slopes. For example soils with a vertic A horizon can only be found on slopes <9º or <10% and duplex soils cannot be found on slopes >20º or >22%. Slope percentage data was extracted from the field descriptions in the land type survey data. The different master horizons were found at slope percentages ranging from -9 to 99% as illustrated in Figure 4.10. However the -9% slopes were not used as that is used as a symbol that shows that there was no data recorded on slope percentage on that point.

4.3.2.2.1 O horizon

The O horizons were restricted to areas with 1 and 2% slopes (Figure 4.10). This is probably because the formation of an O horizon occurs only in conditions where organic material can accumulate. These areas are usually under anaerobic conditions or at places of high altitude which are cold and can hold water thus slowing down organic matter mineralization (Soil Classification Working Group, 1991; Le Roux *et al.,* 1999). With the interaction of other soil forming factors such as temperature and aeration, less than 2% slopes allowed for the accumulation of high levels of soil organic carbon.

4.3.2.2.2 A horizon

The A horizons were found at slope percentages ranging from 0 to 99 % as shown in Figure 4.10. A horizons with lowest (0.40% C) and highest (5.79% C) organic carbon contents occurred at slopes of 14% and 49%, respectively. Single observations were done at these two levels. Therefore to reduce biasness due to very low observations, comparison was put between the 3.50% slopes (n = 3) which had a low organic carbon content on 1.24% and very steep slopes of 70% (n = 3) with a high organic carbon content of 4.71%. The 3.50% slopes and the 70% slopes reveal a rough picture that shows that there was a positive correlation between organic carbon and slope percentage which correlates with the findings of Sims & Nielsen (1986) who discovered that an increase in altitude led to an increase in organic carbon in A horizons. This may be because of a possibility of increased deposition of coarse sediments at lower slopes which leads to increased leaching of nutrients which results in the low nutrient status associated with lower slopes (Moges & Holden, 2008). Le Roux *et al.* (1999) also stated that organic material is reduced as slope percentage increases. The lower temperatures at higher slope percentages also hinder microbial activity, therefore promote organic C storage (Sims & Nielsen, 1986).

The highest number of A horizons occurred at slope percentages of less than 10% (Table 4.3). They ranged from 361 at 2% slopes to 112 at 10% slopes. The number of A horizons decreased as slope percentage increased. The danger of erosion increases as slope percentage increases (FitzPatrick, 1983) therefore this explains that the soils found at level or slightly sloping areas are less affected by soil erosion. Sensitivity to soil erosion also depends on the interaction of factors such as soil type, soil texture, slope length, and slope type (White, 2006). The results also show that most of the soils at a higher elevation do not have A horizons, most likely because soils on steep mountain slopes are shallow and sometimes stony due to the removal of the topsoils by erosion (FitzPatrick, 1983).

The organic carbon content of the soils at slopes with the highest number of observations ranged from 1.4% C at 1% slope to 1.8% C at 8% slope (Table 4.3). With reference to Table 4.3 the organic carbon content of the A horizons increased with an increase in slope percentage up to 8% slope.

Table 4.3 Organic carbon content in A horizon in relative to slope percentage

Slope (%)	Organic carbon (%)	Standard error	Count (n)
1	1.41	0.07	350
2	1.51	0.07	361
3	1.52	0.09	284
4	1.41	0.08	163
5	1.58	0.09	179
6	1.74	0.13	125
8	1.80	0.15	113
10	1.56	0.10	112

However, the organic carbon content in the A horizons was affected by the slope percentage even though the picture becomes clearer when the data was separated in order of observations or occurrences. Table 4.3 also shows that there was generally a positive relationship between organic carbon content and slope percentage up to 8% slope with an exception of soils at 4% slope where there was a slight decrease. The decrease was probably caused by a change in the type and amount of vegetation or a change in the management practices which contributes a lot to the addition of soil organic matter (Havlin *et al.,* 1999). Organic carbon content at slopes of 1%, 2%, 3%, and 4% was not significantly different. At a slope of 8% organic carbon content was not significantly different from the organic carbon content at the 10%, 6%, 5%, and 4% slopes but was significantly higher than at the 1%, 2%, and 3% slopes.

4.3.2.2.3 E horizon

The E horizons occurred at slopes ranging from 0 to 80% (Figure 4.10). There were no E horizons at slopes in depressions or slopes < 0%. The highest organic carbon content of 2% was found in E horizons at a sloping land of 30% and the lowest of 0.20% at moderately sloping areas of 14%.

Most observations of the E horizons were found at slopes of less than 10% as shown in Table 4.4. The number of observations of the E horizons decreased as the slope percentage increased up to 80% with some slopes having single observations such as the 14, 16, 18, 50, 60, 65, and 80% slopes. Most E horizons (n = 40) were formed at areas with a slope less than 2%. The formation of E horizons entails saturation of the subsoil by water which eventually leads to the removal of materials such as clay and organic matter (Soil Classification Working Group, 1991). According to the results, less than 2% slope was suitable for the formation of the E horizon. The results also revealed that the removal of materials such as organic carbon from the E horizons decreased as the slope increased since the amount of organic carbon increased as slope percentage increased. However the pattern is clearer at slopes of less than 10% except for the 7% slopes where there was an abrupt decrease in soil organic carbon. This decrease might have been a result of the low number of E horizons which are not representative. The organic carbon content on the 10% slopes was not significantly different from the organic carbon content on the 8% and 4% slopes but was significantly higher than on the 7%, 6%, 5%, 3%, 2%, and 1% slopes. The differences in organic carbon content on the slopes may be a result of different land use practices, vegetation type as well as climate (Carter, 1996).

Table 4.4 Number of observations of the E horizon in different slopes

Slope (%)	Organic carbon (%)	Standard error	Count (n)
1	0.41	0.04	25
2	0.43	0.04	40
3	0.48	0.07	32
4	0.66	0.09	33
5	0.48	0.08	32
6	0.43	0.07	22
7	0.25	0.05	8
8	0.57	0.11	23
10	0.77	0.11	19

4.3.2.2.4 B horizon

The slope percentages associated with the B horizon ranged from 0 to 99% (Figure 4.10). Different levels of organic carbon were found at different slopes with the highest being 2.15% C at 90% slope and the lowest being 0.28% C at 65% slope. The high organic carbon content at the steep slopes of 90% may be a result of lower soil temperatures which cause less mineralization of soil organic matter by microbial activity (Sanchez, 1976). Microbial activity is usually less at lower temperatures (FitzPatrick, 1983). The 65% slopes probably had the lowest organic carbon content because of soil erosion. Furthermore the upper slopes where soil erosion is prevalent have less organic carbon content than lower slopes where the eroded material is deposited (Ritchie *et al*., 2007; Wang *et al*., 2008). The presence of vegetation cover probably lessened the adverse effect of erosion on soil organic carbon on the 90% slopes. A thick vegetation cover tends to promote soil accumulation more than soil loss even on very steep slopes (FitzPatrick, 1983). Very few observations of the B horizon were noted at areas of high elevation which can be a sign of minimal development of the soils at high elevations (Soil Classification Working Group, 1991).

At sloes less than 10% the organic carbon content range from 0.46 to 0.70% (Table 4.5). When comparing the number of B horizons at such slopes, the highest number were at the 1 and 2% slope levels. The number of observations decreased gradually as the slope increased from 1 to 2%. In general the organic carbon content also increased as the slope increased from 1 to 10% showing evidence of a lower decomposition rate and probably the availability of vegetation cover also aids in the higher accumulation of organic carbon (Havlin *et al.,* 1999). The standard error bars revealed that the organic carbon content between the 1% slope and the 2 to 20% slopes was not significantly different.

Table 4.5 Number of observations of the B horizon in different slopes

Slope (%)	Organic carbon (%)	Standard error	Count (n)
1	0.70	0.30	612
2	0.48	0.02	612
3	0.46	0.01	477
4	0.51	0.02	277
5	0.53	0.03	225
6	0.71	0.06	192
8	0.65	0.04	189
10	0.64	0.05	134

4.3.2.2.5 G horizon

The G horizon is formed under anaerobic conditions where saturation takes place for a long time except if the water is removed unnaturally or by nature (Soil Classification Working Group, 1991). This justifies why the highest number of observations was reported in areas of 1% (n = 14) and 2% (n = 15) slopes since these soils have higher water tables and are generally poorly drained (White, 2006). The organic carbon content ranged from 0.20% at 9% slopes to 2.55% at 1% slopes as shown in Figure 4.10. Surprisingly a G horizon was found at a moderately sloping area of 20%. The formation of a G horizon on the 20% slope may be because of the slope type and terrain of the area. A concave slope may influence an area to be able to hold water, therefore providing conditions that may represent a valley bottom which may promote the formation of a G horizon. With the exception of the G horizon at the 20% slope no G horizons were found at slopes >9%. There was no significant difference in organic carbon content of the G horizons from the various slopes. The error bars reveal a large variation in organic carbon content on the 1% slopes. This may have been caused by the differences in temperature, precipitation, vegetation type as well as the carbon content in the organic material (Tate, 1992a; Carter, 1996) found on the 1% slopes distributed in different areas around South Africa.

4.3.2.2.6 C horizon

Soils that have a C horizon were found at slopes of 0% to 99% (Figure 4.10). The highest organic carbon contents were found at slopes of 6% (0.55% C) and 15% (0.54% C) while the lowest organic carbon content was found at a slope of 13% (0.10% C). Differences in organic carbon contents between slopes were not significant due to large variation within slope levels.

Like the previously mentioned horizons, most observations of the C horizons occurred at areas of lower elevation. In a range of 1% to 12% slopes the highest number of observations was at the 1% slope level (n = 126) and the lowest at the 12% slope level (n = 9). The number of C horizons decreased with an increase in slope except for the 9% slope level which has only 4 observations.

Table 4.6 also showed that there was no particular pattern followed by the organic carbon content in the C horizons. Organic carbon increased as slope increased from 0% to 3% slope and then started to fluctuate as slope percentage increased further. The organic carbon content of the C horizon is very low when compared to the A, E, and B horizons, except at the 6% slope level. This could probably be because it is mainly made up of weathering parent material that has different characteristics from these overlying master horizons (Soil Classification Working Group, 1991). Horizons that are found near the soil surface are usually strongly influenced by microbial activity and have the highest amount of soil organic matter as compared to horizons occupying the lower positions (FitzPatrick, 1983).

4.3.2.2.7 R horizon

The R horizon was found only at 1, 2, and 3% slopes (Figure 4.10). Organic carbon content ranged from 0.10% at a 3% slope to 0.42% at a 2% slope. The organic carbon content at the 1% slope was not significantly different from the organic carbon content at the 2% slope. Appearance of hard rock is evidence of thin soils (Soil Classification Working Group, 1991). This may have been caused by a removal of the overlying horizons by erosion which is normally not very high at slopes less than 3%, which mean it might have taken a very long period of time for the hard rock to protrude. The exposure of hard rock may also be because of an interaction of several factors such as human activities and natural conditions resulting in land degradation and loss of nutrients such as soil organic matter (Jones *et al.,* 2004a).

Table 4.6 Number of observations of the C horizon at different elevations

Slope (%)	Organic carbon (%)	Standard error	Count (n)
0	0.20	0.03	19
1	0.21	0.01	126
2	0.24	0.02	122
3	0.32	0.03	68
4	0.28	0.04	24
5	0.21	0.02	38
6	0.55	0.19	32
7	0.22	0.04	12
8	0.29	0.05	32
9	0.11	0.03	4
10	0.21	0.04	15

Slope percentage had a great effect on the occurrences of the different master horizons. Most observations of the master horizons were made at lower slopes other than at higher slopes where soils are prone to weathering, erosion and leaching. The O and the G horizons were the only ones which had high organic carbon contents at almost level areas, whereas the organic carbon contents in the A, E, B, and C horizons generally increased with an increase in slope to approximately 10%. Few exceptions occurred that coincided mostly with a decrease in the number of observations. The results correlate with the findings of Hontoria *et al.* (1999) who found that there was a positive correlation between soil organic carbon and slope gradient. The amount of soil organic carbon fluctuates more as slope percentage increased.

The results were not in line with that of Ritchie *et al.* (2007) who reported that soil organic carbon decreased as the gradient of the slope increased. Wang *et al.* (2008) also agreed that there was significantly less soil organic carbon in the upland sloping areas where erosion is active when compared to the soils in the lower level areas where deposition is dominant. The pattern of increasing organic carbon content with slope percentage was revealed only on slopes of less than 10% with a few exceptions. Some master horizons were limited to certain slopes. The O horizon was never found at slopes greater than 2%. The R was limited to slopes ranging from 1 to 3%. The G horizon occurred mostly at slopes of 1 to 8% and rarely at slopes of 9 to 20%.

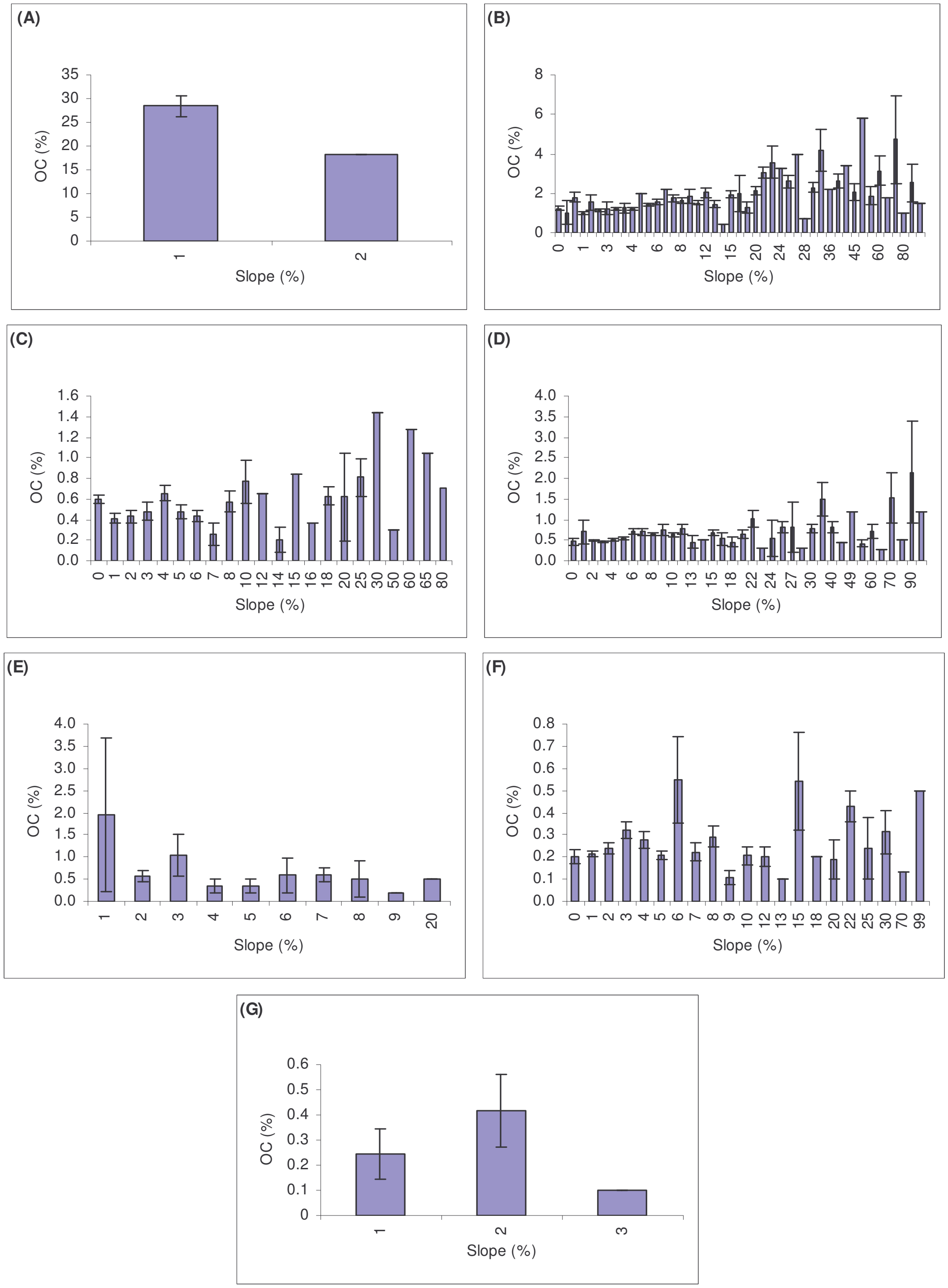


Figure 4.10 Organic carbon content in relation to slope percentage in the master horizons: O horizon (A), A horizon (B), E horizon (C), B horizon (D), G horizon (E), C horizon (F), and R horizon (G)

4.3.2.3 Slope type

Land characteristics such as slope elevation and slope aspect dominate the factors that influence soil organic carbon levels (Rezaei & Gilkes, 2005). Buol *et al.* (1989) stated that the difference in landscape characteristics which includes slope percentage, aspect, and elevation influences the chemical properties of the soil and plant growth. They also state that the landscape attributes influence plant nutrients and vegetation by controlling organic activity. Slope type is normally expressed in terms of its shape. The curves differ according to the environment and influences the way the land is utilized. A slope can either be straight, wavy, terrace, convex, or concave in shape (Le Roux *et al.*, 1999). Le Roux *et al.* (1999) stated that knolls are mostly convex shaped, midslopes are concave shaped while crests and valley bottoms are straight. The slope type data was taken from field descriptions in the land type survey data. Different horizons were found in areas of different slope types in South Africa.

4.3.2.3.1 O horizon

Soils that have an O horizon were found only in convex and concave slopes (Figure 4.11). In the O horizons the average organic carbon content ranged from 18.3% in convex slopes to 28.4% in concave slopes. Organic soils are formed in areas that allow build-up of materials rich in organic matter under saturation for long periods of time (Soil Classification Working Group, 1991). Concave slopes are characterised by less gradient slopes which allow for the accumulation of eroded soil particles (Ritchie *et al.,* 2007) which may be high in organic carbon content depending on the material being eroded. Erosion has adverse effects on soil organic carbon (Honotoria *et al.,* 1999). Most of the O horizons (n = 3) were found on concave slopes and only one was found in convex slopes. Unfortunately not many O horizons were recorded, probably because they have not yet been studied in depth and are not widespread in South Africa (Soil Classification Working Group, 1991)

4.3.2.3.2 A horizon

The A horizon was found in soils situated in straight, concave, and convex slopes (Figure 4.11). On average organic carbon content was 1.26%, 1.51%, and 1.74% on the straight, concave and convex slopes respectively. The highest organic carbon content was thus on the convex slopes. This correlates with the results of Ritchie *et al.* (2007) who reported higher soil organic carbon content on convex slopes when compared with concave slopes. However expectations were that the highest organic carbon content would be from A horizons in concave slopes because of the possibility of accumulation of organic carbon from the above steep slopes as well as the decrease in the rate of soil erosion which increases with slope angle. The difference in organic carbon content between all the slope types was significant. The straight slopes had the lowest organic carbon content. This is probably because deposition of coarse particles is high on straight slopes and less organic material is produced on sandy soils (Kadeba, 1977; Moges & Holden, 2008).

The number of observations of A horizons were also high at convex slopes (n = 707) followed by straight (n = 634) and lastly the concave slopes (n = 399). The high organic carbon content at the convex slopes was probably due to more C inputs such as plant remains on the convex slopes thus contributing higher organic material (White, 2006). Due to a high rate of soil erosion in sloping areas (FitzPatrick, 1983) which are mostly convex shaped higher organic carbon contents were not expected on convex slopes. Steep areas have the highest rate of erosion (Ritchie *et al.,* 2007). High numbers of A horizons were found on convex slopes.

4.3.2.3.3 E horizon

The E horizons were found in straight, concave, and convex slopes (Figure 4.11). On average organic carbon content of the E horizons ranged from 0.42% in the concave slopes to 0.66% in the convex slopes. The straight slopes had an average organic carbon content of 0.46%. The organic carbon content between the straight and concave slopes was not significantly different. On the other hand the organic carbon content on the convex slopes was significantly higher than the organic carbon content on the straight and concave slopes.

Most of the soils with E horizons were found in convex slopes (n = 105) followed by straight (n = 95) and then in the concave slopes (n = 68). The removal conditions found in convex sloping areas which are well drained favoured the formation of E horizons. There is a higher rate of interflow due to increased gradient on convex slopes thus producing a suitable environment for the formation of E horizons (Le Roux *et al*., 1999).

4.3.2.3.4 B horizon

The organic carbon content in the master B horizons ranged from 0.62% on the concave slopes to 0.80% on straight slopes as illustrated in Figure 4.11. Convex slopes had an organic carbon content of 0.70%. The highest organic carbon content was found on the straight or level slopes because they cater for illuvial conditions that prevail in the B horizons.

Most soils with underlying B horizons were found in areas with convex slopes (n = 814) and the least in areas with concave slopes (n = 455). A total of 755 B horizons were found on straight slopes. The difference in organic carbon content between the three slope types was not significant.

4.3.2.3.5 G horizon

The G horizons were found on straight, convex and concave slopes (Figure 4.11). On average organic carbon content was highest in G horizons in concave slopes at 2.37%. A key requirement of G horizon formation is the build up of organic matter and clay under less oxygenated conditions (Soil Classification Working Group, 1991), which require long periods of water saturation. The concave slopes allow for the retention of water and a decrease in microbial activity due to prevailing anaerobic conditions, therefore allowing the accumulation of organic matter. This justifies the high organic carbon found in G horizons in concave slopes. The lowest amount of organic carbon was found on straight slopes at 0.65%. Soils on straight slopes had low organic carbon content probably because of more leaching of soil organic carbon or higher soil temperature which caused an increase in the rate of organic matter mineralization leading to lower levels (Alvarez & Lavado, 1998; Moges & Holden, 2008). The organic carbon content between all the slope shapes where the G horizons were found was not significant. Most G horizons were formed on straight slopes (n = 29) and least on convex slopes (n = 9). The concave slopes had 13 G horizons.

4.3.2.3.6 C horizon

The C horizons were found in concave, convex, and straight shaped slopes (Figure 4.11). On average organic carbon content was highest in straight slopes (0.37%) and lowest on concave slopes (0.26%). The convex slopes had an average organic carbon content of 0.31%. Thus low organic carbon content in the C horizons was recorded. Even though the organic carbon content was different for the C horizons found on the different slopes it was not significant. The highest number of soils with C horizons were reported on straight slopes (n = 130) and lowest on concave slope (n = 71) with the convex slopes in between (n = 120).

4.3.2.3.7 R horizon

The R horizon was found under soils occurring on concave, convex, and straight slopes (Figure 4.11). On average organic carbon content ranged from 0.10% on concave slopes to 0.38% on straight slopes. Hard rock is normally a sign of thin soils depending on the depth on which they are found (FitzPatrick, 1983). It is normally exposed in areas where soil erosion is active. The organic carbon content between the convex and straight slopes was not significantly different. The absence of vegetation and the cultivation of lands found on straight areas may have resulted in the vulnerability of the soil to erosion (Havlin *et al.,* 1999), therefore leading to the exposure of hard rock. Surprisingly some organic carbon content was extracted from the hard rocks on the straight or level slopes and it was higher than in the convex slopes although not significant. The organic carbon content found on the rocks may probably be caused by the occurrence of calcium containing minerals which guards soil organic matter against decomposition (Sanchez *et al.,* 1989). The organic carbon content on the convex and straight slopes was not significantly different.

The highest organic carbon content in the A and E horizons was found in the convex shaped slopes. Organic carbon contents on the convex slopes in both the A and E horizons were significantly higher than on the concave and straight slopes. The highest number of observations in these horizons were also found on the convex shaped slopes. However, the convex slopes which are mostly in sloping areas favour the formation of the A and E horizons by allowing the eluvial conditions that are prevalent in these horizons even though there is accumulation of organic matter in the A horizon. The accumulation may be due to higher production of plant residues which add organic carbon to the soil (Christensen, 1996). The A horizons on concave slopes had a significantly higher organic carbon content than on straight slopes. However, there was no significant difference of organic carbon in the E horizons on concave and straight slopes.

The B and C horizons, being underlying horizons, did not show the same pattern. The highest organic carbon content was from the samples taken from the straight slopes. The lowest organic carbon content was found on the concave slopes. The organic carbon on the straight slopes was significantly higher than on the other slopes for the C horizons but there were no significant differences for the B horizons on all slopes. The highest number of observations in the B and C horizons was from the convex and straight slopes respectively.

Organic carbon accumulation in the O and G horizons was favoured on the concave slopes where the highest amount of organic carbon was found although it was not significant. Ritchie *et al.* (2007) also reported that soil organic carbon content of the soils found on concave slopes had a higher soil organic carbon content than soils found on convex slopes. These soils also had less soil loss than soils in convex slopes. This is proven in the fact that the A and E horizons which had the highest organic carbon on convex slopes had a lower organic carbon content than the O and G horizons that were found in concave slopes.

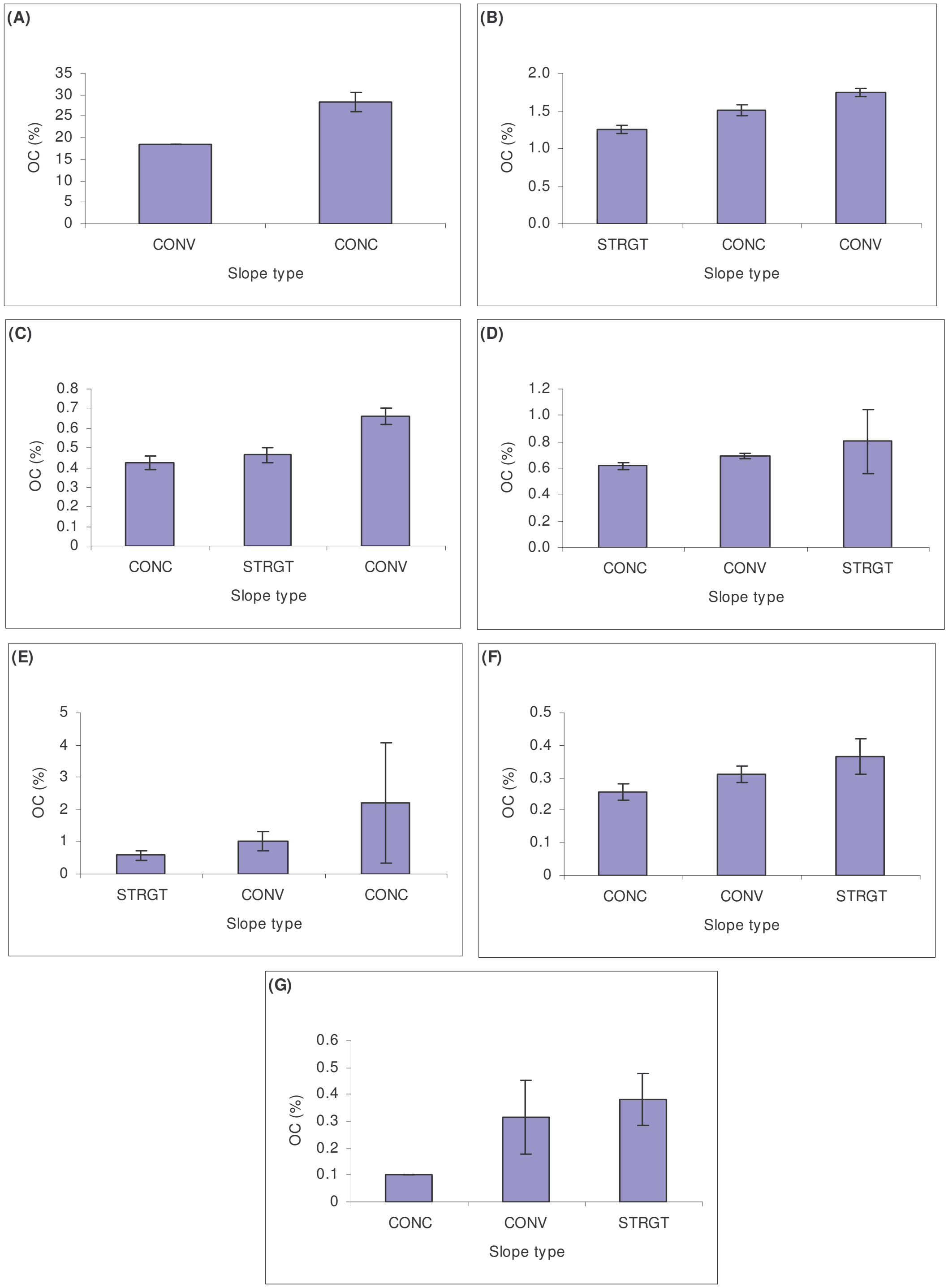


Figure 4.11 Organic carbon content in relation to slope type in the master horizons: O horizon (A), A horizon (B), E horizon (C), B horizon (D), G horizon (E), C horizon (F), and R horizon (G)

The concave slopes offered suitable conditions for the formation of the O and G horizons. This means that the O and G horizons that happen to have a higher organic carbon content than all the other horizons were found in slopes with a low gradient *i.e.* not steep and are concave. This may be because the concave slopes are less steep which shows a relationship that allows the slowing of runoff which in turn allows the deposition of eroded materials and accumulation of nutrients such as organic carbon (Ritchie *et al.,* 2007).

The R horizon is made up of consolidated rock and it can only be seen as proof of shallow soils which are expected to be found in steep convex sloping areas where soil erosion is high (FitzPatrick, 1983; Soil Classification Working Group, 1991). The difference in organic carbon of the hard rocks found on all slopes was not significant.

4.3.2.4 Slope aspect

The aspect of the slope affects the amount of soil organic carbon by affecting the micro-climate of the area *i.e.* moisture and temperature regimes (Carter, 1996; White, 2006). As a result it determines the type of soils formed as well as their nutrient status. A slope can either face north, south, east, west, or at any angle between the four main cardinal points. In South Africa the soils found in the southern and eastern slopes are colder and wetter when compared to soils found in the northern and western slopes which are warmer and drier (Le Roux *et al.,* 1999). The slope aspect data was taken from the land type survey data as described in the field. There was a great diversity on where the different master horizons in South Africa were found with respect to slope aspect.

4.3.2.4.1 O horizon

Soils with an O horizon were restricted to the west and level slopes (Figure 4.12). Although western slopes are known to be warmer and drier (Le Roux *et al.,* 1999) an organic carbon content of 18.3% was recorded. The warmer conditions on the western slopes probably caused increased biomass production which contributed to the build-up of soil organic carbon. High vegetation cover as well as lack of activities that break up the soil may also have contributed to the formation of an O horizon in a western slope. The O horizons on level slopes had a very high organic carbon content of 28.4%. Most of the O horizons were found on level slopes. Level slopes are actually able to hold water for longer therefore providing anaerobic conditions which promote the build up of organic matter by inhibiting the survival and activity of micro-organisms responsible for organic matter decomposition. Level slopes are usually depositional areas and the decrease in soil erosion may result in the accumulation of soil organic carbon. Ritchie *et al.* (2007) reported significantly higher organic carbon levels on depositional areas as compared to upland areas where erosion is high. Soils on lower slopes receive more water which may be stagnant at times (Moges & Holden, 2008) which might provide the anaerobic conditions which inhibit microbial activity.

4.3.2.4.2 A horizon

The A horizon was recorded in soils with; level, west, south, north west, north east, south east, north, south west and, east aspects (Figure 4.12). Their organic carbon content ranged from 1.18% on level slopes to 2.40% on the eastern slopes. The difference may be caused by decreased microbial activity in the eastern slopes because of lower temperatures and hence higher moisture content thus being unsuitable for survival of microorganisms which decompose soil organic matter. Therefore soil organic matter tends to increase under cool moist environments (Jones *et al*., 2004a)

The average organic carbon content of the A horizons found on the southern slopes (1.45%) was expected to be higher than on the northern slopes (1.78%) because of higher decomposition of organic matter in the northern slopes. These averages between the northern and southern slopes differed significantly. The northern slopes were also expected to have lower organic carbon content than the north eastern and south eastern slopes even though the difference was not significant.

4.3.2.4.3 E horizon

The organic carbon content of the E horizons ranged from 0.40% in the south western slopes to 0.68% in the south eastern slopes as illustrated in Figure 4.12. The increase in organic carbon content from the south western, level, southern, northern, western, and eastern up to the north western slopes was not significantly different. The organic carbon content on the north eastern and south eastern slopes was high and not significantly different. The highest organic carbon content was recorded in north eastern and south eastern slopes probably due to higher water content and cooler conditions associated with eastern slopes which lessen microbial activity therefore leading to the accumulation of organic carbon.

The organic carbon content between the northern and southern slope was anticipated to be significantly different but the results were probably influenced by the management practices on soils found on these slopes. The eastern and the western slopes were also expected to be significantly different with the eastern slopes having a higher organic carbon content but possibly the higher moisture content associated with the eastern slopes contributed a lot to the removal conditions common in the E horizons.

The most observations of soils with E horizons were in the northern slopes (n = 66) and the least in the south western slopes (n = 10) and north western slopes (n = 11). Surprisingly the northern slopes had a higher occurrence of soils with E horizons.

4.3.2.4.4 B horizon

The B horizons in South Africa had an organic carbon content ranging from 0.53% in the north western slopes to 0.98% in the southern slopes (Figure 4.12). Preservation of organic carbon in the B horizons found in north western slopes was low because the dry warm conditions that exist in these slopes allowed effective activity of microbes which therefore led to a decrease in soil organic carbon content. The southern slopes are colder and moist thus leading to the conservation of soil organic carbon.

The organic carbon content of B horizons between the other slopes namely: north western, north eastern, west, level, south eastern, and south western was not significant. However the difference was significant in soils found in the eastern and western slopes. The eastern slopes (0.67%) had a higher organic carbon content than the western slopes (0.57%).

4.3.2.4.5 G horizon

The highest organic carbon content in the G horizons was recorded on the slopes facing east (0.63%), north east (0.68%), and south east (0.68%) as illustrated in Figure 4.12. It seems the conditions that exist on eastern slopes of low temperature and high moisture content had a positive impact on the conservation and accumulation of organic carbon in the G horizons. The accumulation of clay in the G horizons coincided with high moisture content on the eastern slopes and lead to poor drainage conditions. This resulted in poor aeration which is not suitable for the survival of microorganisms (Soil Classification Working Group, 1991; Jones *et al.,* 2004a). Conditions are thus favourable for the build up of soil organic matter on the eastern slopes due to slower decomposition. There is no significant difference in organic carbon content between the northern, north western, eastern, north eastern, and south eastern slopes. Most of the G horizons were recorded on the western slopes (n = 90) followed by the southern slopes (n = 85). The lowest numbers of G horizons were recorded on the level slopes (n = 19).

4.3.2.4.6 C horizon

The highest organic carbon content in the C horizons was found in soils situated on the eastern slopes (1.01%) as shown in Figure 4.12. The lowest amount was in soils on the south eastern slopes (0.23%). The organic carbon content found in the south eastern, western, north western, south eastern, and north eastern slopes was not significantly different. Although the difference was not significant the south eastern slopes were expected to have a higher organic carbon content than the western slopes because decomposition is slower due to lower soil temperatures on the south eastern slopes. Soil organic matter decomposition increases as temperature increases (Kirschbaum, 1995). The southern slopes were not expected to have a lower organic carbon content than the northern slopes even though the difference was not significant. The western slopes had a significantly lower amount of organic carbon when compared to the northern and eastern slopes. Most of the C horizons were recorded in soils on the western (n = 136) and southern slopes (n = 102).

4.3.3.4.7 R horizon

The organic carbon content of the hard rock ranged from 0.30% in the western slopes to 0.40% in the eastern and level slopes (Figure 4.12). Even though water penetration is nearly impossible in hard rock, the effect of slope aspect was evident as the wetter eastern slopes had the highest organic carbon content. The organic carbon content in the western, northern and southern slopes was not significantly different. Most hard rocks were found on the southern and western slopes where the number of observations of hard rock was higher than on the other slopes.

The aspect of slope had a great effect on the organic carbon content of soil master horizons in South Africa. Highest organic carbon content was on the eastern slopes for the A and C horizons, on the southern slopes for the B horizons, south eastern slopes for the E and G horizons, level slopes for the O horizon, and on the western slope for the R horizon. The southern and eastern slopes seemed to have a positive impact on the accumulation of organic carbon content.

Thus there is slower microbial activity on the south easterly slopes which leads to a build up of soil organic matter. When comparing all the master horizons the highest organic carbon content was reported in the O horizon (28.4%) on level slopes which allow for the accumulation of organic material especially if there is dense of vegetation cover.

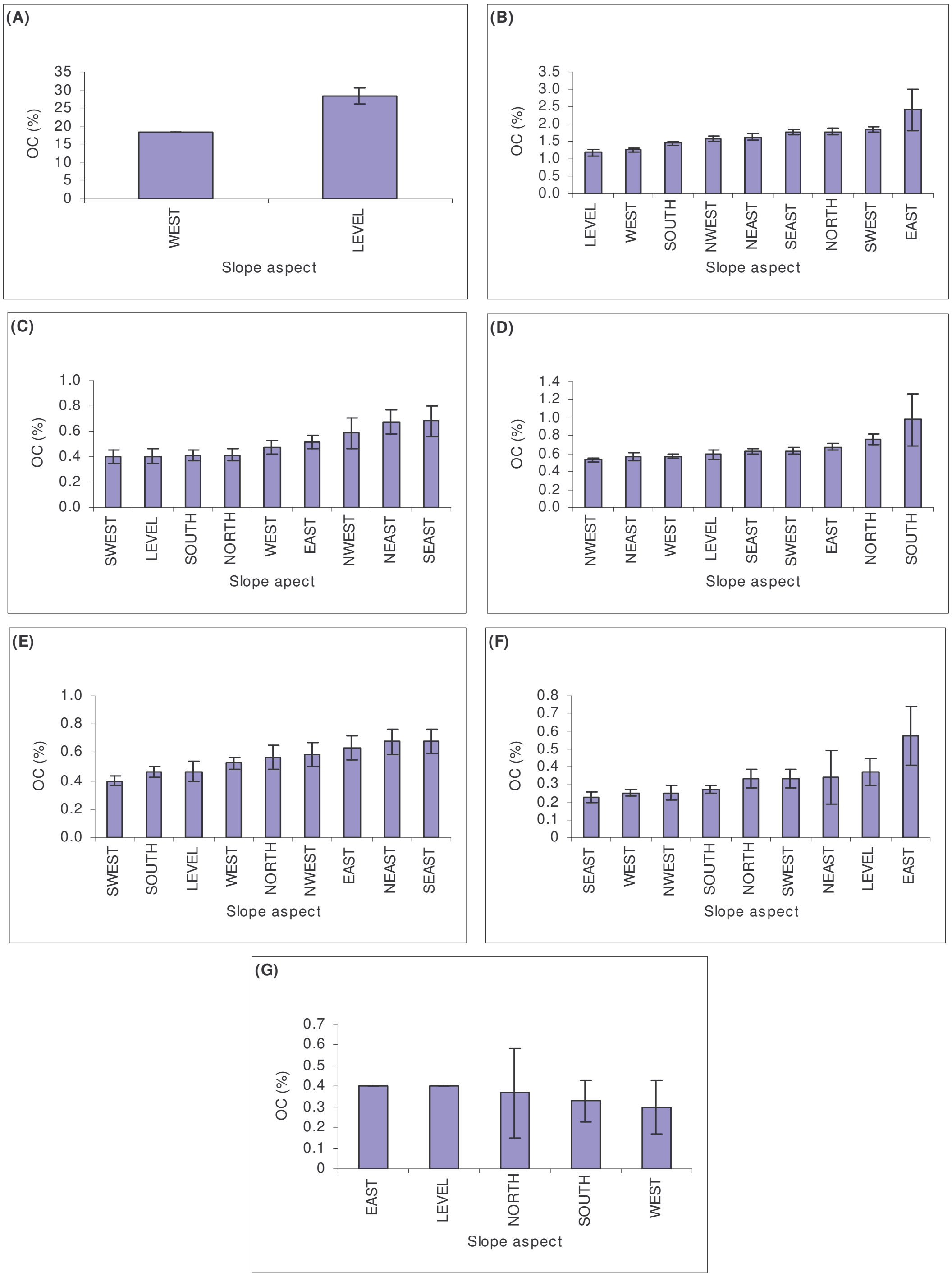


Figure 4.12 Organic carbon and slope aspect relationship between in soil master horizons: O horizon (A), A horizon (B), E horizon (C), B horizon (D), G horizon (E), C horizon (F), and R horizon (G)

4.3.3 Clay content

Tate (1992a) stated that even though climate is the principal factor in controlling the amount of carbon in soil, texture is also very important as it can overtly influence the storage of soil carbon. Emphasis was put on the clay content because it strongly influences the chemical characteristics of the soil. Christensen (1996) also reported higher carbon levels in clay than silt which proves that clay is more efficient in carbon conservation. The amount of clay in the soils determines the rate at which the soil can retain minerals since the cation exchange capacity (CEC) and organic matter content of the soil depend on the clay content (Moges & Holden, 2008). Anderson *et al.* (1981) also stated that the texture of the soil influences soil organic carbon content by playing a vital part in shielding of soil organic matter against decomposition. Therefore there is a very important relationship between clay and organic carbon content. The clay content of the different modal profiles was extracted from the physical properties table in the land type survey data. Graphs were drawn and the correlation coefficient (R^2) calculated, in order to determine the relationship between clay content and organic carbon in the soil.

4.3.3.1 O horizon

The relationship between organic carbon and clay content (R^2 = 0.44%) was better than in the other master horizons although it was not enough for any conclusions to be drawn from it (Figure 4.13). About 56% of variability was left unexplained by the data. The O horizon being an organic horizon had the highest amount of organic carbon (32.60% C) which was found in a soil with a clay content of 7.90%. Unlike in the other master horizons the relationship between organic carbon and clay content was negative.

4.3.3.2 A horizon

There was a poor correlation between clay and organic carbon content (R^2 = 0.24) in the A horizon as illustrated in Figure 4.13. The highest clay content recorded in the A horizon was 77% with an organic carbon content of 1.50%. However, a relationship between the two variables was very weak. The highest organic carbon content in the A horizons was 21.90% C with a clay content of 20.40%. Due to high mineral retention properties associated with clay particles it was expected that the highest clay percentage would give the highest organic carbon content but the results revealed the opposite.

4.3.3.3 E horizon

Clay and organic carbon content also showed a weak relationship in the E horizon (Figure 4.13). The correlation coefficient of 0.29 was very low. This horizon is eluvial, therefore a high amount of clay was not expected but a maximum of 68.40% was reported. Instead there is normally of buildup of quartz or other resistant minerals of silt or sand in the E horizon instead of clay (Soil Classification Working Group, 1991).

4.3.3.4 B horizon

There was absolutely no correlation between clay content and the amount of organic carbon in the B horizons (R^2 = 0.07; Figure 4.13). It was not expected because the B horizon is illuvial (White, 2006), the high amount of clay received from the overlying horizons was expected to help in the retention of more organic carbon. According to Angers and Carter (1996), soil organic matter increases as clay content increases.

In the B horizons lowest organic carbon content was 0.10% C with a clay content of 8%, and highest organic carbon content was 8.10% C with a clay content of 31.70%. Interestingly the highest clay content of 88.50% had an organic carbon content of 0.90% C which was very low since the B horizon with the highest clay was expected to have a reasonably high organic carbon content. This may be because of poor decomposition of plant material and organic material due to low soil temperatures (Sanchez, 1976) in these soils leading to lower organic material in the overlying horizon.

4.3.3.5 C horizon

The C horizons exhibited a maximum clay content of 74.10% with an organic carbon content of 0.40% C. In the C horizon with the lowest clay content, namely 0% an organic carbon content of 0.10% C was reported. However, the correlation between organic carbon and clay content (R^2 = 0.04) was very poor (Figure 4.13).

4.3.3.6 G horizon

High clay content was expected in the G horizons (84.50%) since this horizon has not undergone any removal of organic matter and clay, instead there has been accumulation (Soil Classification Working Group, 1991). However, there was absolutely no relationship between organic carbon and clay in this horizon (R^2 = 0; Figure 4.13). The presence of clay can therefore not be associated with organic carbon in these horizons.

4.3.3.7 R horizon

There was no association between organic carbon and clay content in the R horizon (R^2 = 0.04; Figure 16). The highest clay content was 45.20% which had an organic carbon content of 0.10% C whilst the lowest clay content of 0.90% also had an organic carbon content of 0.10% C. This proves that there was no particular relationship between clay and organic carbon content.

Particle size distribution can control the level of soil organic carbon regardless of the climate prevailing in that area (Alvarez & Lavado, 1998). Unfortunately that relationship was not supported by this data. The highest correlation between organic carbon and clay content was found in the O horizon (R^2 = 0.44), but was negative, whilst the lowest was found in the G horizon (R^2 = 0). The relationship was poor for all the horizons. This corresponds with the study of Sims & Nielsen (1986) who reported r values of -0.19 to 0.12. These results also correlate with the findings of Hontoria *et al.* (1999), who reported that the relationship between soil organic carbon and texture (including clay content) was not significant. The correlation coefficient values in this study seemed to decrease in the order: O, E, A, B, C, R, and G horizons.

The results revealed that as the clay content increased the amount of organic carbon in the O horizons decreased which meant that they were negatively related in the O horizon. An explanation can be found in the research of Spain (1990) where he discovered that carbon was not only weakly correlated with clay content but the relationship was also negative in soils formed on basaltic parent materials. Kadeba (1977) explains that the effect of soil texture on soil C is highly influenced by parent material. This shows the importance of the interaction of these factors combined with other factors that affect organic carbon content of the soil such as parent material, land use practices and temperature.

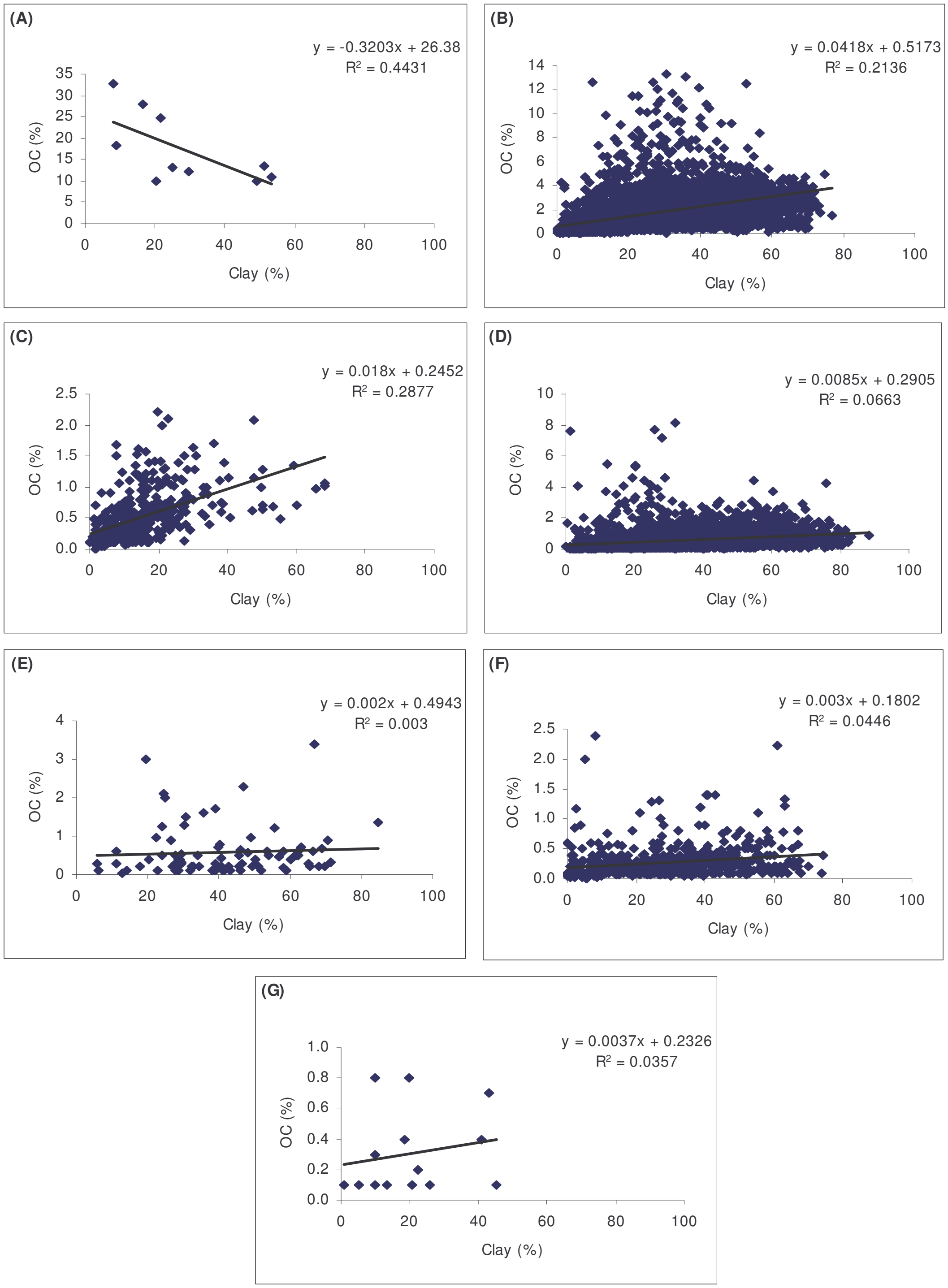


Figure 4.13 Effect of clay on organic carbon content in the soil master horizons: O horizon (A), A horizon (B), E horizon (C), B horizon (D), G horizon (E), C horizon (F), and R horizon (G)

4.3.4 Estimating soil organic carbon in soil master horizons

A model that could help in estimating the level of soil organic carbon in soil master horizons was developed using Microsoft Excel (2003). All the countable variables that play a vital role in soil formation that were available in the database were used. The variables included climate (rainfall, evaporation, and aridity index), topography (slope percentage and slope aspect), and soil texture (clay).

After determining the correlation of the different variables to organic carbon individually, the variables were combined and a regression was done to determine any improvements from the previous results. All the data set points with missing data were deleted. During the development of the model, the variables with a correlation coefficient greater than 0.01 were added to the model.

The results in Table 4.7 show that there was a better correlation in some horizons between the variables when grouped together rather than when they used individually. Correlation coefficients decreased from the O horizon to the C horizon. The highest R^2 of 1 was found in the O horizon with clay content and rainfall being the variables that contributed significantly to the model. Individually the variables clay content and rainfall gave a R^2 of 0.44 and 0.03 respectively. This shows that the combination of the variables yielded positive results by improving the R^2. The relationship between organic carbon content with rainfall and clay was negative in the O horizons.

There was a 50% correlation between organic carbon and aridity index, clay content and slope percentage in the A horizon (Table 4.7). The variables all contributed positively to the model. Even though the R^2 improved when all three variables were used it was still not high enough for the model to be used to estimate soil organic carbon in the A horizons in South Africa.

Aridity index, clay content, and slope percentage contributed positively to estimating organic carbon in the E horizons of South Africa. The correlation coefficient even though not high enough (R^2 = 0.44), was better than when their relationship was determined separately (aridity index: R^2 = 0.11; clay: R^2 = 0.29). Unfortunately, the contribution of the other variables was very poor. An R^2 of 0.55 was found in the R horizon (Table 4.7). The variables that made the greatest impact were aridity index and slope aspect.

Unfortunately the correlation coefficients of the B, C, and G horizons were very poor at 0.18, 0.03, and 0.16 respectively. The use of all the variables failed to improve the relationship between organic carbon and the variables. According to Table 4.7 aridity index (6 times) and clay content (5 times) seemed to have affected soil organic carbon content more than the other variables with regard to their occurrences. Aridity index affected soil organic carbon content positively in the A, E, B, and R horizons and negatively in the C, O, and G horizons. Clay content also affected the A, E, and B horizons positively whilst it affected the O and G horizons negatively. But surprisingly the individual effect of clay content on organic carbon in the G horizon (Figure 4.13), was positively correlated.

Table 4.7 Estimating organic carbon in the soil master horizons of South Africa

Horizon	Correlation coefficient (R^2)	Observations (n)	Model
A	0.50	2674	$Y = -1.96 + 10.98X_3 + 0.03X_4 + 0.01X_5$
E	0.44	329	$Y = -1.85 + 6.68X_3 + 0.02X_4 + 0.01X_5$
B	0.18	3113	$Y = 0.14 + 1.34X_3 + 0.01X_4$
C	0.03	512	$Y = 0.54 - 1.18X_3$
O	1	4	$Y = 48.86 - 0.02X_1 - 0.57X_4$
G	0.16	58	$Y = 8.80 - 0.01X_1 - 21.31X_3 - 0.06X_4 - 0.06X_5 - 0.01X_6$
R	0.55	14	$Y = 1.00 + 6.38X_3 - 0.05X_5$

Where: Y = Carbon percentage

X_1 = Rainfall

X_2 = Evaporation

X_3 = Aridity index (AI)

X_4 = Clay

X_5 = Slope percentage

X_6 = Slope aspect

4.4 Conclusions

Soil organic carbon content varies widely in the master horizons of South African soils. The average organic carbon decreased in the following sequence; O, A, R, G, B, E, and C horizons. It ranged from 15.98% C in the O horizon to 0.27% C in the C horizons. The surface horizons (O and A) had the highest soil organic carbon content probably because of the availability of plant cover or vegetation which led to the accumulation of organic material. Soil organic carbon is generally reduced with depth (Spain, 1990; Oades, 1995), because of more additions of carbon in the topsoils (Alvarez & Ladavo, 1998). Alvarez & Lavado (1998) added that normally “the upper soil layer receives organic matter from the aboveground net primary production and a greater portion of the root production”. However, the soil organic carbon content in the O horizons was significantly higher than in all the other master horizons.

It was very difficult to determine the relationship between soil organic carbon and climatic variables in South Africa. Kern *et al.* (1998) also discovered that the relationship between soil organic matter and climatic variables at a relative large scale was weak. In South African soils, soil organic carbon was positively correlated with rainfall and aridity index in the A, E, B, C, G, and R horizons but was negatively correlated with evaporation. The O horizon showed a negative correlation with rainfall and aridity index whilst the correlation was positive with evaporation. The low correlation coefficient values may also be caused by the error term and the natural variation that is found between the sampling sites (Dai & Huang, 2006). Other factors that may have lead to the low correlation include the type of vegetation, level of soil erosion, topography, climate or instability that occurred in the soil that are known to have an effect on soil organic matter (Hontoria *et al.,* 1999).

The terrain morphological units influenced soil organic carbon as well as on the formation of the different master horizons. The highest amount of soil organic carbon in the O horizons was found at the valley bottom, with 1% slope and concave shape. This corresponds with the findings of Burke *et al.* (1999) who reported that the most significant topographic influence on soil organic matter was found in the foot slopes which had the largest amount when compared to the midslopes and the summits. Most of the O horizons were discovered at the footslopes, with a slope percentage of 1 and concave shape with a level orientation in terms of aspect. The highest organic carbon content in the A horizons was found at the upper midslopes of 49% that are convex shaped and facing east. The A horizons were mostly formed in high numbers on the midslopes of 2% with a convex shape that are oriented to the south.

The midslopes of 2% and convex shape that are usually facing north offered the most suitable conditions for the formation of the E horizon. The highest organic carbon content in the E horizons was found in the upper midslopes with a convex shape and south east direction. The B horizons at the southern scarps that are straight shaped had the highest organic carbon content while most of them were formed at the upper midslopes facing south. Similar to the B horizons, the C horizons are on the scarps but on the eastern slopes had the highest organic carbon content and most of them were formed at the foot slopes and at slopes of 1% facing west.

The highest numbers of G horizons were formed at the valley bottom and straight slopes that are facing south whereas the highest organic carbon content in the G horizons was found at the valley bottom with 1% slope and concave shape in the south easterly direction. Lastly, the hard rock on the crests with a straight shape and 2% slope with a level direction had the highest organic carbon content. Most of the hard rocks were found at the midslopes with an equal number on the convex and straight slopes that are facing either west or south.

In general, the colder and wetter conditions on the south eastern slopes offered the most suitable conditions for the accumulation of soil organic carbon in the A, E, B, C, and G horizons. The level slopes gave the highest organic carbon content in the O and R horizons. The master horizons were found in the highest numbers at slopes of 1% to 2%.

The correlation between soil organic carbon and clay content of the soil master horizons decreased gradually from the topsoils to the subsoil horizons with the O horizons having the highest. The soil organic carbon and clay content relationship could only explain 44%, 21%, and 29% of variability in the O, A, and E horizons respectively as well as 6%, 4%, 0.3%, and 4% of variability in the B, C, G, and R horizons respectively. These results prove that organic carbon content in the soil master horizons is not significantly influenced by clay content.

Multiple regression models with different combinations of rainfall, evaporation, aridity index, clay, slope percentage, and slope aspect could explain 50% and 100% variability in the surface horizons (A and O) whilst only 3% to 55% could be explained in the remaining subsurface horizons. Soil organic carbon could be explained by rainfall and clay in the O horizon. Aridity index, clay content and slope percentage described the soil organic carbon in the A and the E horizons while in the B it was affected by aridity index and clay only. The C horizon was influenced by aridity index. The pattern of organic carbon content in the G was described by more variables namely; rainfall, aridity index, clay content, slope percentage and slope aspect. In the R horizon organic carbon was influenced by aridity index and slope percentage. Depending on the correlation of the climate factors, terrain attributes and clay with soil organic carbon, can be used to predict the level of soil organic carbon on the landscape (*e.g.* O horizon) thus contributing to the progression of C sequestration models as well as appropriate land use management systems. Unfortunately this can not be done for all the master horizons of South Africa because of low correlations.

CHAPTER 5
ORGANIC CARBON CONTENT IN DIAGNOSTIC SOIL HORIZONS OF SOUTH AFRICA

5.1 Introduction

The dominant soils of South Africa differ considerably from each other. After the identification of the master horizons, there are different characteristics that are specific within them. However, these specific properties of the master horizons are very important in thoroughly defining them. The South African Soil Classification system (Soil Classification Working Group, 1991) was developed to help describe in “fairly rigorous terms a number of diagnostic horizons and materials” that can be used for classifying the soils that are found in South Africa. Formation of these diagnostic horizons and materials may be affected by different factors depending on their location. The factors of soil formation: climate, parent material, vegetation and topography, all interact to give the diverse character of South African soils (Jenny, 1941). The content of soil organic carbon varies significantly per diagnostic horizon.

Soil organic matter is a vital constituent of soil that influences the chemical, biological, and physical properties of it and is also the major source of carbon (Carter, 1996). However, intense changes in land use practices such as cultivation of virgin lands have led to abrupt decreases in soil organic matter levels (Scotney & Dijkhuis, 1990; Stevenson & Cole, 1999). The soil forming factors also highly contribute to the variability of soil organic matter (Jones *et al*., 2004a).

Carter (1996) stated that the ability of a soil to store organic matter depends on several factors that include: the type of soil and landscape, vegetation type, soil management, and the climate of the area. He further stated that the effect of climate can be refined by the association between annual precipitation as well as mean annual temperature. In wet and cool climates the rate of soil organic matter decomposition decreases and favours its accumulation whereas in dry warm climates the rate of decomposition of soil organic matter is high (Tate, 1992a). The topography of an area can also affect soil organic matter levels by controlling the microclimate of the area across the landscape (Carter, 1996; White 2006). The texture of the soil particularly the clay content has also been found to affect the organic carbon levels of the soil (Burke *et al*., 1989; Alvarez & Lavado, 1998; Jobbagy & Jackson, 2000)

To understand the dynamics of organic carbon in South African soils, the relationship between organic carbon and the factors that influence its conservation and sequestration in the diagnostic horizons and underlying materials in South Africa was investigated. This was done with the help of the land type survey data (Land Type Survey Staff, 2003). Main emphasis was directed to the relationship between soil organic carbon with the main soil forming factors climate and topography. The effect of soil texture on soil organic carbon was also explored. The study was done with a hope that at the end there could be way in which the amount of soil organic carbon in the diagnostic horizons and materials in South Africa could be estimated.

5.2 Procedure

A total of 31 diagnostic horizons and underlying materials were described in the land type survey data. The land type survey started in 1970 and a large number of profiles were analysed for physical and chemical properties (Land Type Survey Staff, 2003). The diagnostic horizons and materials were shown in Table 3.5. Only the data points with organic carbon content of more than zero were used and those with missing organic carbon data were deleted from the database. Based on the Binomial Soil Classification System for South Africa (MacVicar *et al.,* 1977), which was used for the land type survey, and the Taxonomical Soil Classification System for South Africa (Soil Classification Working Group, 1991) the gaps where diagnostic horizon data was missing were filled by reference to the soil forms. For consistency a list of underlying materials (Table 3.4) was compiled to help fill in the gaps.

Unfortunately, some data points did not have sufficient data and were deleted from the database. The "*om*" diagnostic horizon was also discovered in the database and because the designation could not be identified that horizon was removed from the database. The contribution of the overburden was found to be insignificant and it was also removed from the database. According to MacVicar *et al.* (1977) and the Soil Classification Working Group (1991), an organic O topsoil has to have at least an organic carbon content of 10%. Therefore all topsoils with an organic carbon content of less than 9% but were classified as diagnostic organic O were deleted from the database. A total of 29 diagnostic horizons and materials were then used to study the behaviour of organic carbon in the diagnostic horizons of South Africa. Approximately 11 640 samples of soil diagnostic horizons, taken mainly from virgin soils were available.

The organic carbon data were analyzed statistically by calculating the mean, standard error, 25th percentile, median, and 75th percentile for each diagnostic horizon and underlying material. Then the effect of climate (rainfall, evaporation, and aridity index), topography (terrain morphological units, slope percentage, slope type, and slope aspect) and soil texture (clay content) was investigated per diagno stic topsoil horizon (Table 5.1). For this exercise, based on the criteria formulated by Fey (2009), the diagnostic subsoil horizons and underlying materials were grouped into silicic, calcic, duplex, podzolic, plinthic, oxidic, gley, and inceptic soils. The inceptic soils were further divided into the cumulic and lithic subgroups (Table 5.1). This soil grouping was done based on the subsurface horizons and features as the identifying characteristics. The symbols for the diagnostic horizons are given in Table 3.5. The climate records were extracted from climatic records in the South African Atlas of Climatology and Agrohydrology (Schulze, 2006). The topographical features were taken as described in the field.

Table 5.1 Diagnostic horizons and underlying materials (adapted from: Fey, 2009)

Soil groups		Diagnostic horizons
Organic		Organic O (oo)
Humic		Humic A (ah)
Vertic		Vertic A (ve)
Melanic		Melanic A (ml)
Orthic		Orthic A (ot)
Silicic		Dorbank (db)
Calcic		Soft carbonate B (sc)
Duplex		Pedocutanic B (vp), prismacutanic B (pr)
Podzolic		Podzol B (pz)
Plinthic		Soft plinthic B (sp), hard plinthic B (hp)
Oxidic		Red apedal B (re), yellow-brown apedal B (ye), red structured B (vr)
Gley		G horizon (gh), unconsolidated material with signs of wetness (uw), unspecified material with signs of wetness (on), gleycutanic B (gc),
Eluvial		E horizon (gs)
Inceptic	Cumulic	Neocutanic B (ne), neocarbonate (nc), regic sand (rs), stratified alluvium (al)
	Lithic	Lithocutanic B (lc), hard rock (ro), saprolite (so), unconsolidated dry material (ud), unspecified dry material (od).

The standard error bars were used to test significance of difference as suggested by Cumming *et al.* (2007) which showed that the overlapping of the standard error bars meant the horizons and underlying materials were not significantly different from each other and *vice versa*. They also state that the amount of variation in the data can be revealed by the length of the bars.

Using only the variables of climate, topography, and texture that are discreet, a model to estimate the soil organic carbon in the diagnostic soil horizons was developed by combining all the variables together and doing a regression. Stray data points in the following horizons: vertic A, orthic A, podzol B, soft plinthic B, red apedal B, unspecified material with signs of wetness, gleycutanic B, regic sand, neocutanic B, stratified alluvium, E horizon, pedocutanic B, prismacutanic B, yellow-brown apedal B, unconsolidated material with signs of wetness, neocarbonate B, and unconsolidated material without signs of wetness were not included in the calculation of the correlation coefficient (R^2) in the climate and clay data.

5.3 Results and discussion

The land type survey data contained ultimately reliable organic carbon observations for 5 diagnostic topsoil horizons (Table 5.2) and for 25 diagnostic subsoil horizons and materials (Table 5.3). Organic carbon is one of the most important features that is used to define and distinguish between the topsoils (MacVicar *et al.,* 1977; Soil Classification Working Group, 1991). Amongst the five topsoils the organic O horizon had the highest organic carbon content. The organic carbon content declined gradually in the following order: organic O, humic A, melanic A, vertic A, and the orthic A. Barnard (2000) also reported the same pattern of organic carbon content in his results when using the land type survey data. The average organic carbon content of the topsoils ranged from 20.89% in the organic O to 1.41% in the orthic A.

The topsoil horizons had the highest organic carbon content (Table 5.3). This may be because of the availability of vegetation in the topsoils that has a positive influence on the accumulation of soil organic matter content. Organic matter accumulates to under grass cover (Theron, 1965). A decrease in plant productivity leads to lower organic matter levels (Carter, 1996). The impact of sound management practices that take place highly influences the organic matter levels in topsoils. The organic O horizon has a high amount of organic carbon as a result of the conditions under which it was formed. The conditions most suitable for organic carbon formation include a slow rate of decomposition of plant residues because of long periods of saturation or stagnant water in swamps or ponds (Soil Classification Working Group, 1991). Low temperatures also promote accumulation of organic material through decreased decomposition of organic matter (Kirschbaum, 1995).

The orthic A horizon (n = 5459) had the highest number of observations of the topsoils (Table 5.3). This proves that the most common topsoil is the orthic A horizon. The Soil Classification Working Group (1991) stated that most topsoils in South Africa cannot be associated with the organic O, humic A, vertic A, or melanic A in nature and are therefore referred to as orthic A. According to Hutson (1983) the organic carbon content of the orthic A horizons is <2% which corresponds with the results of the land type survey where the average organic carbon content of the orthic A was 1.41%. The Soil Classification Working Group (1991) also stated that the organic O horizons are not very common in South Africa and that is why only a few of them were found during the survey (n = 6) when compared to the other topsoils.

Table 5.2 Statistical analysis for the diagnostic topsoil horizons

		Organic carbon (%)				
Diagnostic horizons	Count	Mean	Standard error	Minimum	Median	Maximum
Organic O	6	20.89	3.70	9.36	12.90	32.6
Humic A	359	3.68	0.11	0.60	3.09	13.3
Melanic A	411	2.58	0.07	0.40	2.20	9.8
Vertic A	221	1.54	0.08	0.10	1.20	8.4
Orthic A	5459	1.41	0.02	0.01	1.00	21.9

From Figure 5.1it can be deduced that organic carbon content in the organic O horizons was significantly higher than in all the other topsoils. The difference was not significant between the humic A, melanic A, vertic A, and orthic A. Due to a higher clay content associated with the vertic A horizon (Fey, 2009), it was expected to have a higher organic carbon content than the melanic A but, the opposite was true even though it was not significant. Increased clay content is associated with increased organic carbon content because clay has the ability to protect organic compounds from any microbial breakdown (Burke *et al.*, 1989). The length of the standard error bars reveals that the highest variation was in the data of the organic O topsoils.

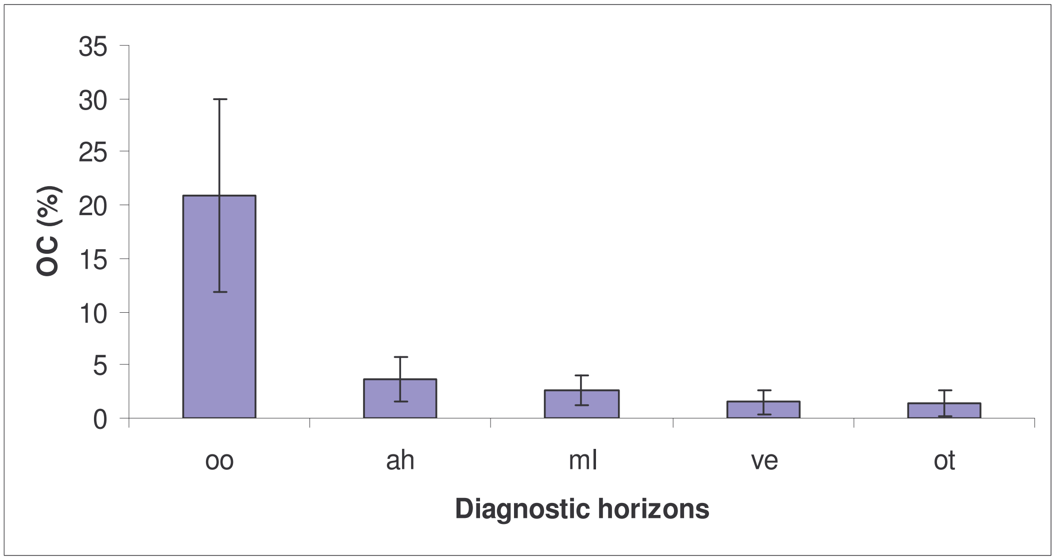


Figure 5.1 Soil organic carbon content in the diagnostic topsoil horizons: organic O (oo), humic A (ah), melanic A (ml), vertic A (ve), and orthic A (ot), with standard error bars

On average organic carbon content of the subsoil horizons and materials in South Africa ranged from 1.18% in the podzol B horizon to 0.15% in the dorbank (Table 5.4). The podzol B horizons probably had the highest organic carbon content because they are normally found in areas under fibrous vegetation and winter or high rainfall (Soil Classification Working Group, 1991; Fey, 2009). Organic carbon is positively related to precipitation and negatively related to temperature (Alvarez & Lavado, 1998). The dorbank had low organic carbon content because it is normally associated with extremely arid conditions (Laker, 2003) which are not suitable for the accumulation of organic matter. Organic carbon is positively correlated with precipitation which means it decreases in dry areas where precipitation is low (Alvarez & Lavado, 1998).

The highest organic carbon content (24.8%) was recorded in the unspecified material with signs of wetness. This may just be an erroneous value. The lowest organic carbon values of 0.01% were found in several horizons, namely pedocutanic B, E horizon, soft plinthic B, red apedal B, and the unspecified dry material. There was no significant difference in the amount of organic carbon in the subsoil horizons and materials as demonstrated in Figure 5.2. The highest standard error in the data was found in the unspecified material with signs of wetness (0.32) as well as in the podzol B (0.34) horizons.

The most common subsurface horizons as indicated in Table 5.3 proved to be the red apedal B (n = 1286) followed by the yellow apedal B (n = 755). The red apedal B was probably the most common, because they are normally found under a wide variety of climatic environment and parent materials (Soil Classification Working Group, 1991).

Table 5.3 Statistical analysis for the diagnostic sub soil horizons and materials

		Organic carbon (%)				
Diagnostic horizons	Count	Mean	Standard error	Minimum	Median	Maximum
Podzol B	23	1.18	0.34	0.05	0.75	7.60
Red structured B	205	0.80	0.04	0.10	0.68	4.20
Neocarbonate B	9	0.70	0.25	0.07	0.49	2.50
Yellow-brown apedal B	755	0.69	0.03	0.02	0.50	7.20
Lithocutanic B	208	0.68	0.04	0.06	0.50	4.10
Pedocutanic B	486	0.61	0.02	0.01	0.50	4.40
Unspecified material with signs of wetness	78	0.59	0.32	0.02	0.20	24.80
G horizon	80	0.56	0.06	0.04	0.42	3.00
Red apedal B	1286	0.54	0.01	0.01	0.40	7.70
Neocutnanic B	351	0.53	0.03	0.02	0.38	8.10
E horizon	403	0.50	0.02	0.01	0.40	2.20
Soft carbonate B	3	0.47	0.19	0.10	0.63	0.70
Stratified alluvium	46	0.46	0.07	0.10	0.30	2.40
Prismacutanic B	260	0.45	0.02	0.02	0.40	3.10
Gleycutanic B	106	0.41	0.07	0.04	0.20	6.20
Soft plinthic B	275	0.34	0.02	0.01	0.30	2.10
Unconsolidated material with wetness	90	0.33	0.07	0.04	0.20	6.10
Hard rock	28	0.32	0.05	0.04	0.20	0.80
Saprolite	82	0.31	0.03	0.06	0.20	2.00
Unspecified dry material	303	0.27	0.02	0.01	0.20	2.10
Hard plinthic	9	0.24	0.06	0.10	0.12	0.50
Unconsolidated material with wetness	6	0.19	0.05	0.05	0.20	0.40
Regic sand	54	0.16	0.02	0.04	0.10	0.90
Dorbank B	2	0.15	0.05	0.10	0.15	0.20

In summary, organic carbon content in the diagnostic topsoil horizons followed this obvious pattern: organic O (20.89%) > humic A (3.68%) > melanic A (2.58%) > vertic A (1.54%) > orthic A (1.41%). The organic carbon content of the topsoils was higher than in the subsoil horizons. Sims & Nielsen (1983) reported that the organic carbon content of soil decreases with depth. However, Barnard (2000) reported that the organic carbon distribution was not as obvious in the subsoils as it was in the topsoils. The results of this study also portrayed the same pattern. The organic carbon content of the subsoil B horizons was lower than of the topsoil A horizons. The soft plinthic B (0.34%), E (0.50%), G (0.56%), hard plinthic B (0.24%), gleycutanic (0.41%), unspecified material with signs of wetness (0.59%), and unconsolidated material with signs of wetness (0.19%) had a lower organic carbon content than the B master horizons (0.59%; Table 4.2). Their association with water was expected to produce higher organic carbon levels than the B master horizons. On the other hand, the structured B horizons like the red structured B (0.80%), pedocutanic B (0.61%), and prismacutanic B (0.45%) had higher organic carbon contents. Barnard (2000) also observed the same pattern with the red structured B, pedocutanic B, and prismacutanic B horizons which had higher organic carbon contents than the B master horizons.

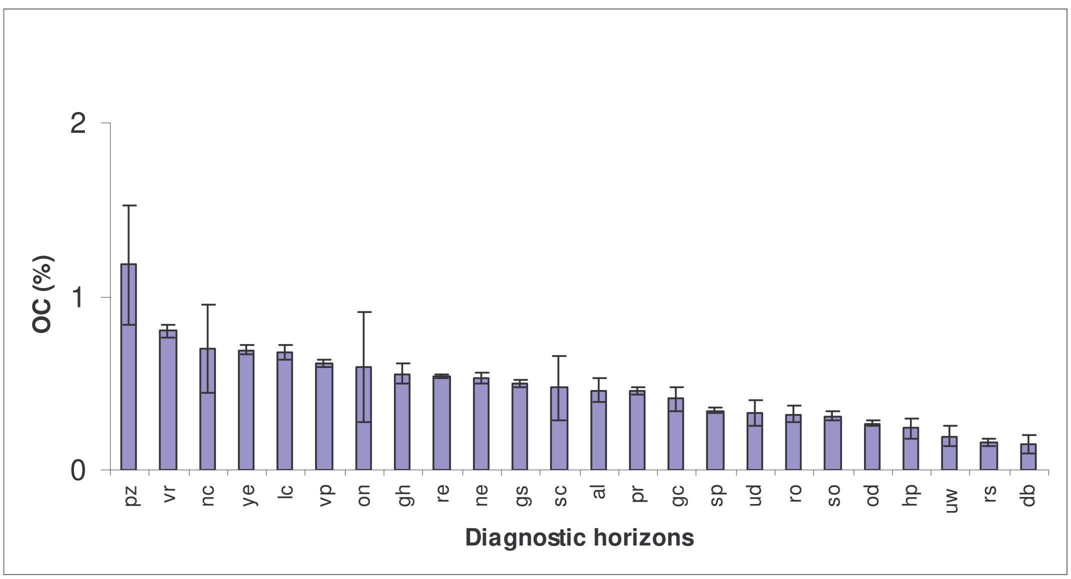


Figure 5.2 Soil organic carbon content in the diagnostic subsoil horizons and materials: podzol B (pz), red structured B (vr), noecarbonate B (nc), yellow-brown apedal B (ye), lithocutanic B (lc), pedocutanic B (vp), unspecified material with signs of wetness (on), G horizon (gh), red apedal B (re), neocutanic B (ne), E horizon (gs), soft carbonate B (sc), stratified alluvium (al), prismacutanic B (pr), gleycutanic B (gc), soft plinthic B (sp), unconsolidated material without signs of wetness (ud), hard rock (ro), saprolite (so),

unspecified dry material (od), hard plinthic B (hp), unconsolidated material with signs of wetness (uw), regic sand (rs), and dorbank B (db) with error bars

5.3.1 Climate

The low soil organic carbon content in the diagnostic soil horizons may be a result of the interaction of several soil forming factors especially climate and parent material (Scotney & Dijkhuis, 1990). Some of the most important indices of climate are rainfall, evaporation, and aridity index. As explained earlier their influence on the organic carbon content in the diagnostic soil horizons is dealt with here and shown in Figures 5.3 to 5.19.

5.3.1.1 Organic soils

The organic soils are characterized by the organic O topsoil. There was a poor correlation (R^2) between organic carbon content and rainfall (R^2 = 0.28) as illustrated in Figure 5.3. The relationship between organic carbon and aridity index explained 50% of the variability. The highest correlation was found between organic carbon and evaporation (R^2 = 0.92). This latter relationship was positive. These results were not expected because evaporation is a result of increased temperatures and temperature is negatively related to soil organic carbon (Tate, 1992a). On the other hand organic carbon content probably increased as evaporation decreased because of more vegetative growth. However, the accumulation of organic carbon can occur only up to a certain temperature, therefore if it continues to rise, organic carbon decomposition will increase rapidly because the conditions will be conducive for mineralization (FitzPatrick, 1983). There was a negative relationship between organic carbon content and rainfall as well as aridity index. An increase in rainfall caused a decrease in the organic carbon content of the organic O horizon. This was not expected because the presence of an organic O horizon means organic material accumulation and sometimes wetting of the soil for most of the year unless it is artificially drained (Le Roux *et al.,* 1999). This prolonged wetness was expected to provide anaerobic conditions that slow down organic matter decomposition (Havlin *et al.,* 1999). As the aridity of the land became higher the organic carbon content of the organic O horizon decreased.

The diagnostic organic O horizon behaved in a similar manner to the O master horizon where organic carbon behaved negatively towards rainfall and aridity index (Section 4.3.1.1). The positive relationship between organic carbon content and evaporation in the organic O horizon also correlates with the behaviour of the O master horizon. However, the opposite was expected for both horizons since for the formation of an organic O horizon there has to be large accretion of organic matter and slower decomposition of plant residues due to the anaerobic conditions caused by long periods of saturation by water (Soil Classification Working Group, 1991). These results correlate with the findings of Spain (1990) who also discovered that organic carbon was negatively correlated to precipitation.

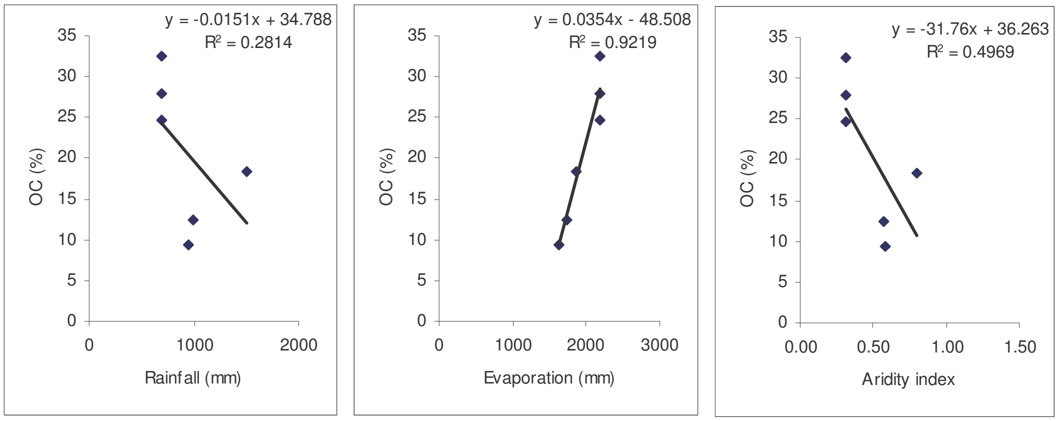


Figure 5.3 Effect of the indices of climate on the organic O horizon

5.3.1.2 Humic soils

Humic soils have a humic A horizon (Fey, 2009). The relationship between organic carbon and rainfall, evaporation, and aridity index was very poor for the humic A horizons (Figure 5.4). The correlation coefficient (R^2) ranged from 0.05 to 0.12. The humic A horizons are characterized by the buildup of large amounts of humified organic matter in wet climates under well-drained conditions (Soil Classification Working Group, 1991; White, 2006). This has been proven by the positive relationship between organic carbon and rainfall in this diagnostic horizon as shown in Figure 5.4. The formation of this diagnostic horizon requires aerobic conditions and free drainage (Le Roux *et al.,* 1999). The activity of soil fauna is high as allowed by those conditions and thus helps to give the properties that the humic A horizons have. They were found in areas with an average rainfall of 1000 mm which is high. The relationship between organic carbon content and evaporation is negative in the humic A horizon. The organic carbon accumulation is a result of the moist conditions in these horizons that allow vegetation growth even during the dry times of the year (Le Roux *et al.,* 1999).

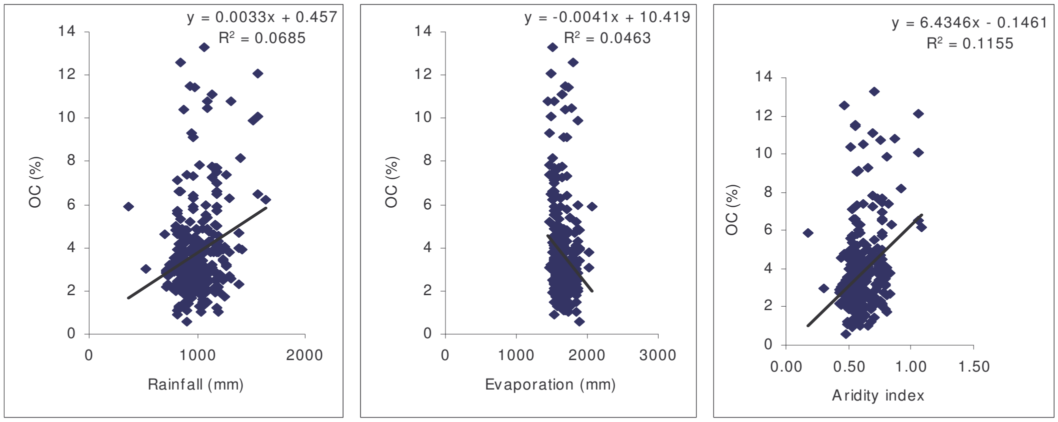


Figure 5.4 The effect of the indices of climate on the humic A horizon

5.3.1.3 Vertic soils

Organic carbon correlated very poorly with rainfall (R^2 = 0.03), evaporation (R^2 = 0.08), and aridity index (R^2 = 0.05) in the vertic A topsoils (Figure 5.5). The organic carbon content in this horizon related positively with rainfall and aridity index while it related negatively with evaporation. Figure 5.5 also illustrates that the vertic A only develops in areas with a low average aridity index of 0.33. These results verify the findings of Le Roux *et al.* (1999) who stated that the vertic A horizons commonly develop under moderate subarid climates.

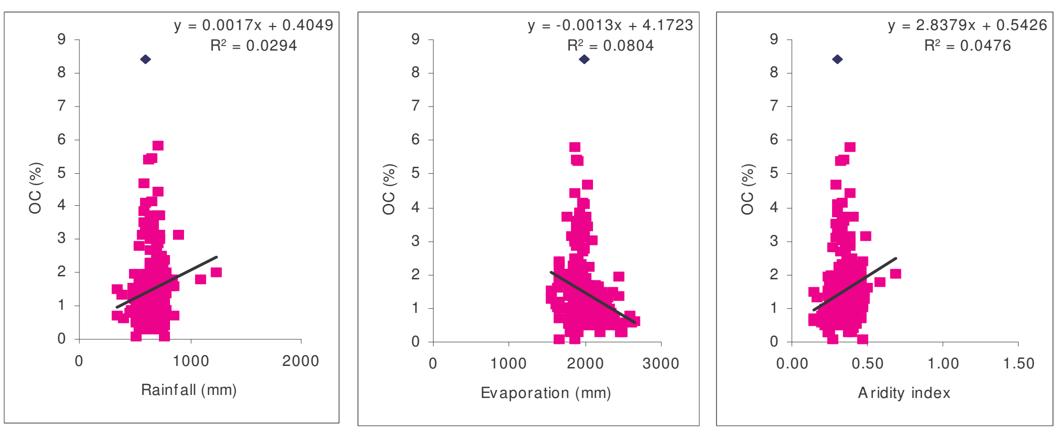


Figure 5.5 The influence of the indices of climate in the vertic A horizon

5.3.1.4 Melanic soils

The correlation between organic carbon content and the elements of climate, namely rainfall, evaporation, and aridity index was very low as illustrated in Figure 5.6. There was a similarity between their correlation coefficient values ranging from R^2 = 0.10 to R^2 = 0.11 which was roughly the same for all variables. However, the relationship between organic carbon and rainfall, as well as aridity index was positive. As precipitation increased there was an increase in organic carbon content in the melanic A horizon. This horizon is formed in areas under sub-humid and humid climates, as well as in semi-arid conditions and cover an area of 2.34 million ha or 2% of South Africa (MacVicar *et al.*, 1977; Soil Classification Working Group, 1991; Le Roux *et al.,* 1999; Van der Merwe *et al*., 2002). Van der Merwe *et al*. (2002) stated that around 82.80% of the melanic A horizons are formed under semi-arid conditions. They also stated that about 75% of the melanic A horizons were formed in areas with rainfall of between 550 mm and 800 mm. This study also revealed that they were also formed in areas with a rainfall as low as 340 mm and as high as 1329 mm.

Evaporation and organic carbon content in this horizon were negatively correlated. An increase in the rate of evaporation caused a decrease in the organic carbon content of the melanic A horizon. This shows that for organic carbon to accumulate in this horizon there has to be moisture available. Moist conditions will probably help to slow down the rate of decomposition of soil organic carbon since microbial activity will be slower (Havlin *et al.,* 1999).

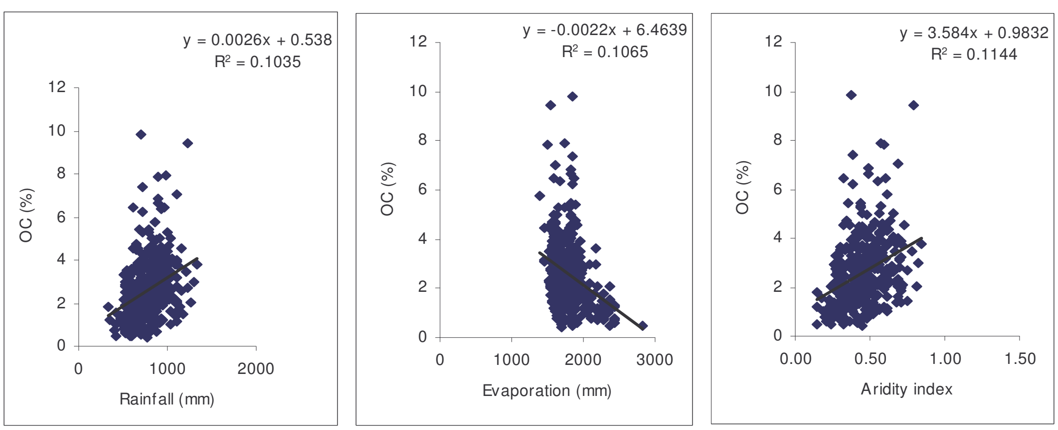


Figure 5.6 The influence of the indices of climate in the melanic A horizon

5.3.1.5 Orthic soils

Rainfall, evaporation and aridity index could only account for 26%, 22%, and 30% of variability when correlated with organic carbon content in the orthic A horizon (Figure 5.7). These correlation coefficient values were still low, even though they were better than the values of the other topsoil horizons except the organic O horizon. The orthic A horizons occur over a wide range of soil forming conditions and they are also known to differ greatly in properties such as organic carbon content (Soil Classification Working Group, 1991).

However, the organic carbon content in these horizons showed a positive relationship with rainfall and aridity index. Organic carbon content related negatively to evaporation in the orthic A horizon.

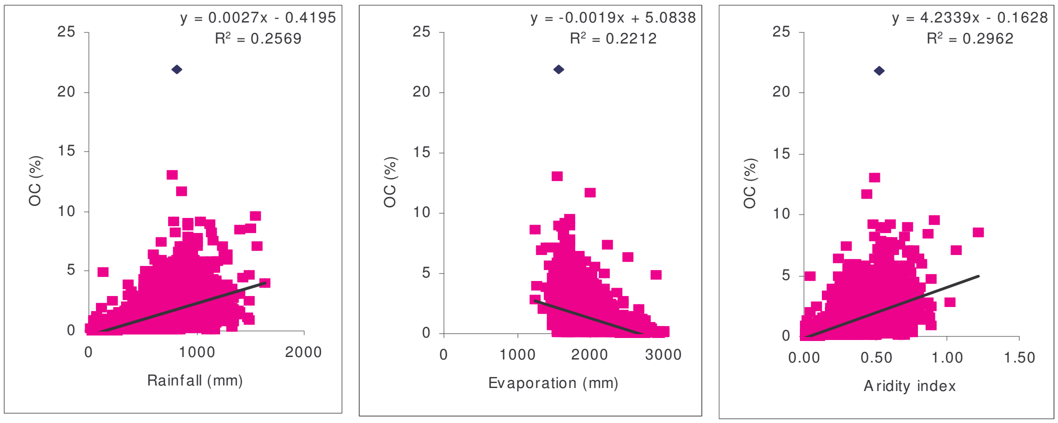


Figure 5.7 The influence of the indices of climate in the orthic A horizon

5.3.1.6 Silicic soils

The dorbank B is one of the recently recognised diagnostic horizons that were included in the Taxonomical Soil Classification System for South Africa (Laker, 2003). It is a horizon characterised by silica concentration of particles and it occurs mostly in the arid parts of South Africa (Fey, 2009). The organic carbon content of this horizon is therefore very low. Arid conditions are associated with warm dry conditions. Organic matter decomposition is high under dry warm conditions since it increases with an increase in soil temperature (Kirschbaum, 1995). Unfortunately, only two data points were identified which precluded statistical analysis (Figure 5.8).

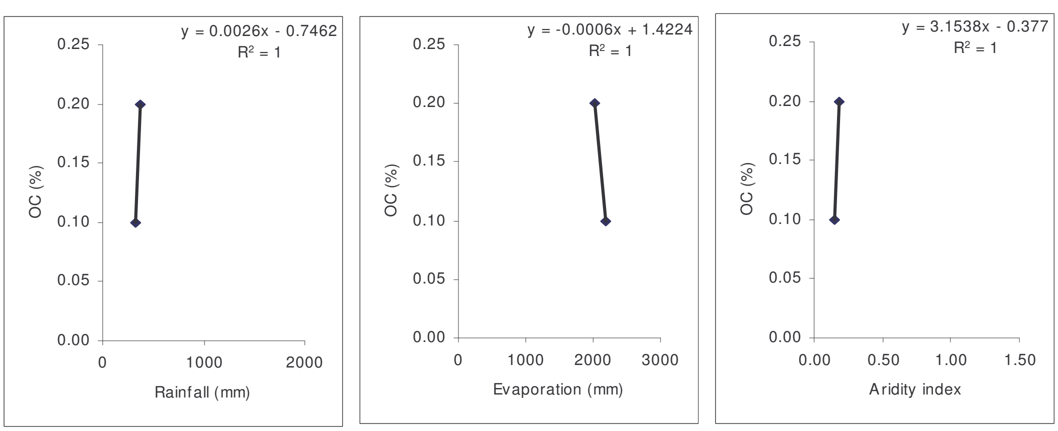


Figure 5.8 Effect of the climate indices on soil organic carbon in silicic soils

5.3.1.7 Calcic soils

The soft carbonate is the characteristic diagnostic horizon for calcic soils. This horizon is found in arid climates and its morphology is dominated by lime (Fey, 2009). Figure 5.9 shows that this diagnostic horizon was found in dry areas with an average aridity index of approximately 0.20. The correlation between organic carbon content and rainfall, evaporation, and aridity index was very high. There is a possibility that they actually do correlate very well and also that the correlation coefficient was very high because not many observations of the soft carbonate were discovered. However, Cumming *et al*. (2007) stated that if the number of observations is high the results will be more correct in estimating the value of the exact population.

In these soils organic carbon related negatively with rainfall and aridity index. On the contrary, it related positively with evaporation. Fey (2009) stated that carbon dioxide and evaporation from respiring living matter are some of the processes that give this horizon its characteristic features such as “pipe stems, nodules, and laminations”. An increase in the amount of carbonates found in this horizon may be responsible for increased soil organic carbon that is found here. The calcium content ($CaCO_3$) in the rocks also helps protect soil organic matter against decomposition (Sanchez *et al.,* 1989). That is probably why organic carbon and evaporation related positively in this soil horizon. The effect of low moisture content did not have the anticipated effect of increasing organic matter decomposition. An increase in rainfall may lead to a decrease in biological respiration which would result in decreased carbon dioxide levels so this may be the cause of a negative relationship between rainfall and organic carbon in the soft carbonate horizon.

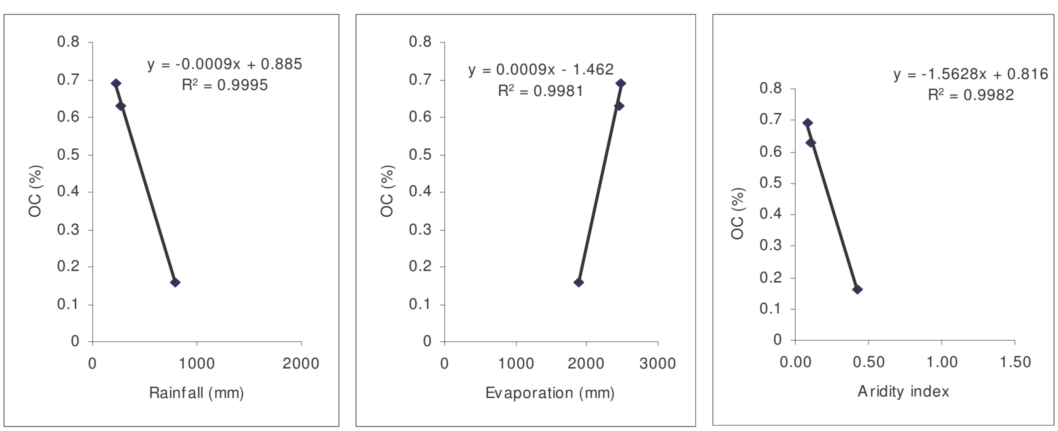


Figure 5.9 Relationship between soil organic carbon and the indices of climate in calcic soils

5.3.1.8 Duplex soils

The duplex soils are characterised by pedocutanic and prismacutanic B horizons. These horizons are known for their high clay content probably resulting from illuviation. They are also found in sub-humid to semi-arid climates (Fey, 2009).

There was a poor correlation between organic carbon and rainfall, evaporation and aridity index for both diagnostic horizons (Figure 5.10). Even though the correlation coefficient values were very low for both horizons, organic carbon correlated better with the indices of climate in the pedocutanic B than in the prismacutanic B horizons. Rainfall and organic carbon content was expected to have a high correlation in these horizons because of their high clay content. Clay particles are known for their effect of protecting organic C from depletion (Christensen, 1996). The relationship was positive between organic carbon and rainfall as well as aridity index. Alvarez & Lavado (1998) also reported a positive relationship between organic carbon content and precipitation. Organic carbon related negatively with evaporation in both horizons. The average aridity index was 0.32 and 0.28 in the prismacutanic B and pedocutanic B horizons respectively. Their presence shows that these horizons are found in semi-arid climates.

5.3.1.9 Podzolic soils

The podzolic soils are defined by the podzol B horizons. Organic carbon content correlated negatively with rainfall and aridity index in this horizon (Figure 5.11). However, the relationship was positive with evaporation. Soils with podzol B horizons are normally found in areas with a winter rainfall and organic matter has built up through illuviation (Soil Classification Working Group, 1991). It was expected that the excess rainfall may affect organic carbon content positively as decomposition tends to be slower, but that did not happen.

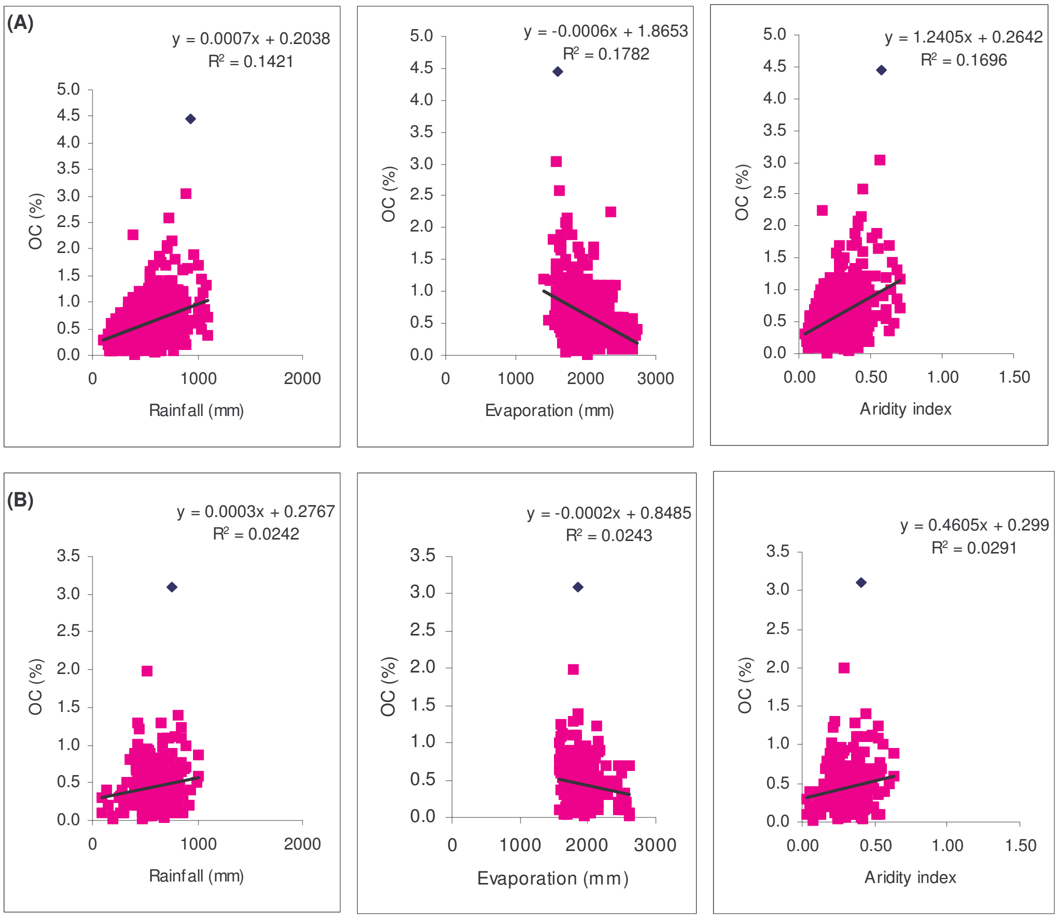


Figure 5.10 Relationship between soil organic carbon and the indices of climate in pedocutanic B (A) and prismacutanic B (B) duplex soils

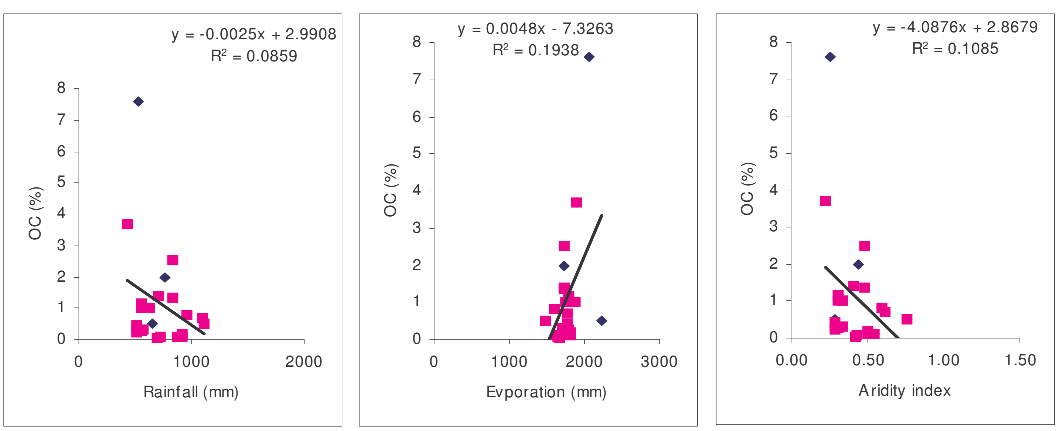


Figure 5.11 Relationship between soil organic carbon and the indices of climate in podzolic soils

5.3.1.10 Plinthic soils

The plinthic soils are distinguished by having either a soft plinthic B or hard plinthic B horizons. These horizons are formed in regions in the profile that are subject to fluctuating water tables (Soil Classification Working Group, 1991). According to Le Roux *et al.* (1999) these soils are formed in sub-humid to humid climates that are warm and have an unpredictable dry season.

The correlation between organic carbon content and rainfall, evaporation and aridity index was very low in both horizons even though there was a slight increase in the correlation coefficient values in the hard plinthic B horizon (Figure 5.12). The correlation coefficient values of the soft plinthic B were approximately 0.02 for all variables and ranged from 0.17 to 0.21 in the hard plinthic B horizon.

Surprisingly, organic carbon content behaved in a different manner in these horizons. The association between organic carbon and rainfall as well as aridity index was positive in the soft plinthic B horizons whereas they related negatively in the hard plinthic B horizons. Evaporation was negatively related to organic carbon in the soft plinthic B horizons but related positively in the hard plinthic B horizons. The horizons were both found in areas with an average aridity index of 0.36. They were therefore formed in semi-arid climates. According to Table 5.4 the average organic carbon content was 0.34 and 0.24% in the soft plinthic B and hard plinthic B horizons respectively. The slightly higher organic carbon content in the soft plinthic B was probably a result of a positive relationship with rainfall that was experienced in this horizon since its formation requires periodic saturation with water. Since the hard plinthic B is a more established version of the soft plinthic (Le Roux *et al.*, 1999), soil forming factors such as time and parent material may have led to the change in behaviour of soil organic carbon when linked to climate, rainfall, evaporation, and aridity index.

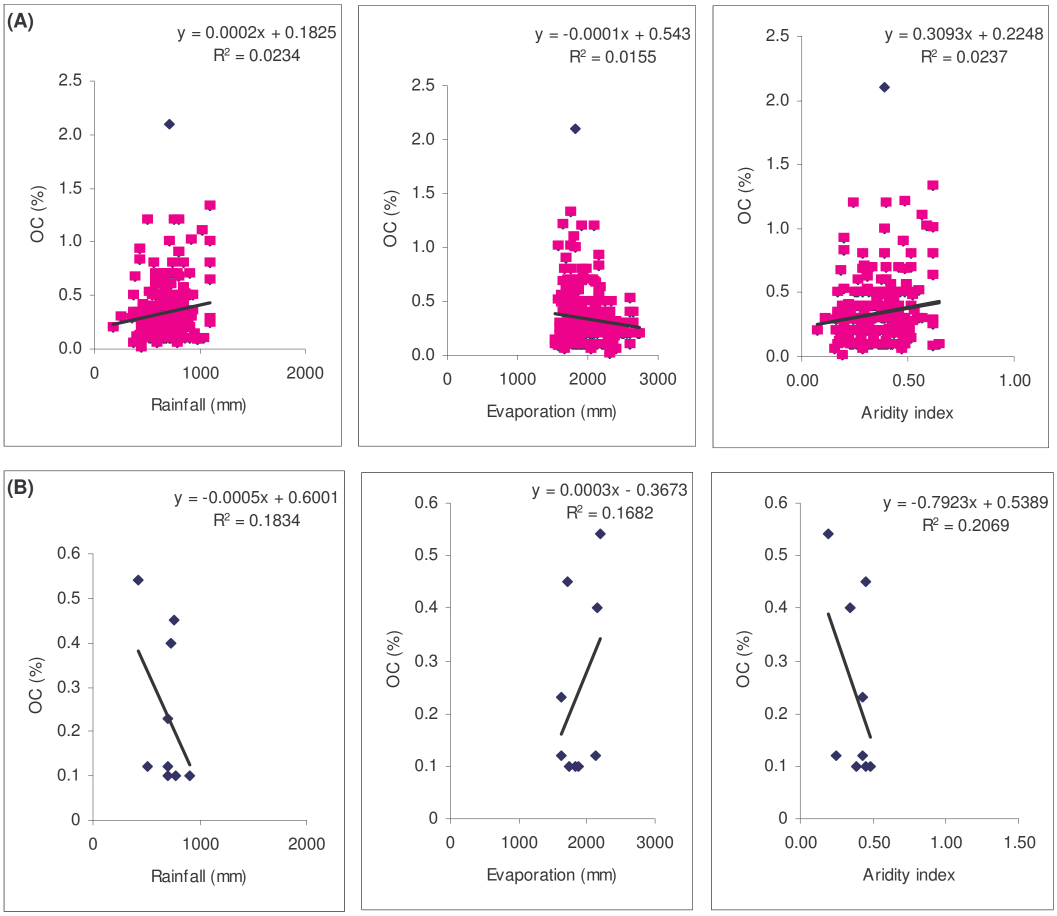


Figure 5.12 Relationship between soil organic carbon and the indices of climate in the soft (A) and hard (B) plinthic soils

5.3.1.11 Oxidic soils

The oxidic soils are characterised by red apedal B, yellow-brown apedal B, and red structured B horizons. These horizons are found in soils that have good internal drainage (Fey, 2009). They are also found under a wide range of climatic conditions (Soil Classification Working Group, 1991).

The correlation between organic carbon content and the indices of climate was very low in the oxidic soils (Figure 5.13). Their correlation coefficient values decreased in the following order: yellow-brown apedal B, red apedal B, and lastly red structured B. In all three diagnostic horizons, organic carbon content related positively with rainfall and aridity index whereas it related negatively with evaporation.

The average aridity index of the horizons ranged from 0.37, 0.38 to 0.41 in the red apedal B, red structured B, and yellow-brown apedal B respectively which means they are mainly found in semi-arid climates. The Soil Classification Working Group (1991) stated that the presence of a yellow-brown apedal B horizon normally indicates a wetter soil moisture regime than the red apedal B horizon. The red structured B horizons had a higher average organic carbon content than the yellow-brown B and red apedal B horizons. The average rainfall was 690, 706 to 750 mm for the red apedal B, red structured B, and yellow-brown apedal B horizons respectively. From the pattern revealed by the aridity index and rainfall average values it is clear that an increase in rainfall lead to increased organic carbon content. A decrease in moisture through evaporation therefore resulted in a decrease in the organic carbon content.

5.3.1.12 Gley soils

The gley soils are characterised by the G horizon (Figure 5.14). Unconsolidated materials with signs of wetness as well as unspecified material with signs of wetness can also be regarded as gley soils since they are all known for their prolonged saturation with water which varies depending on the horizon. These soils were formed in semi-arid climates with an average aridity index of 0.34. Horizons and materials of this nature usually have poor drainage probably because of the underlying material or where they are situated in the landscape (Le Roux *et al.,* 2009)

The correlation between organic carbon content and the factors of climate: rainfall evaporation, and aridity index was poor in all the gley horizons (Figure 5.14) except the good correlation of organic carbon content with evaporation in the unconsolidated material with signs of wetness (R^2 = 0.97). When compared to the other horizons slightly higher correlation coefficient values were found in the unspecified material with signs of wetness with 22% of variability explained by the aridity index. These values were too low for any conclusions to be drawn from them, except with evaporation in the unconsolidated material with signs of wetness.

Organic carbon content was positively correlated with rainfall and aridity index in the G horizons and unspecified material with signs of wetness. This was expected since the accumulation of organic carbon is favoured by anaerobic conditions that are caused by continuous saturation by water. Under anaerobic conditions organic matter decomposition tends to be slow (Havlin *et al*., 1999). This happens because during these conditions microbial activity decreased, therefore causing a decline in the decomposition of soil organic matter. Organic carbon content was negatively related to evaporation.

The unconsolidated material with signs of wetness behaved in a totally different manner. Surprisingly, organic carbon content correlated negatively with all variables. There was practically no correlation between organic carbon content and climate parameters, since the correlation coefficient values were approximately zero. The unconsolidated material with signs of wetness was expected to behave in the same manner as the other gley soils. According to Table 5.3 the number of observations of the unconsolidated material with signs of wetness (n = 6) was very low so probably that was not enough for the relationship between organic carbon and climate to be expressed by the data.

5.3.1.13 Eluvial soils

The E horizon is known for its eluvial characteristics. There is a lot of nutrient loss by luviation including the removal of humus thus resulting in a grey colour of the E horizon (Soil Classification Working Group, 1991). Only 11, 18, and 15% of variability could be explained by rainfall, evaporation and aridity index in the E horizon (Figure 5.15). This horizon was found in semi-arid areas with an average aridity index of 0.40.

Rainfall and aridity index correlated positively with organic carbon content whereas it related negatively with evaporation. Even though an increase in rainfall was expected to cause increased eluviation of organic carbon probably by leaching, it seemed to have a counter effect on organic carbon content. Evaporation is associated with warm temperatures. Therefore higher evaporation increases mineralisation of organic matter thus resulting in reduced organic carbon levels that is why their relationship was negative. Tate (1992a) also reported decreased organic matter levels as temperature increased as it reduces soil moisture.

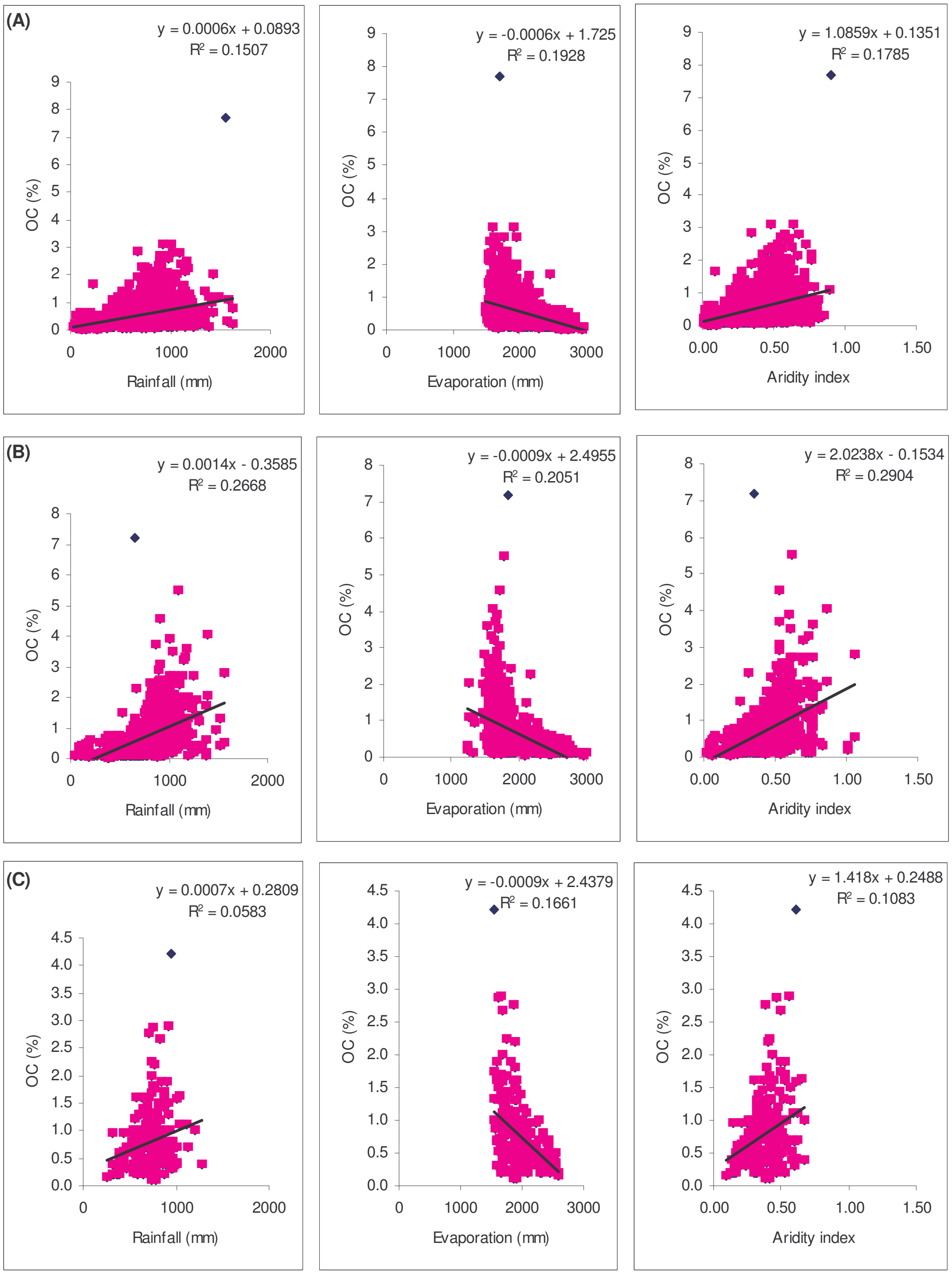


Figure 5.13 Relationship between soil organic carbon and the indices of climate in oxidic red apedal B (A), yellow-brown apedal B (B), and red structured B (C) horizons

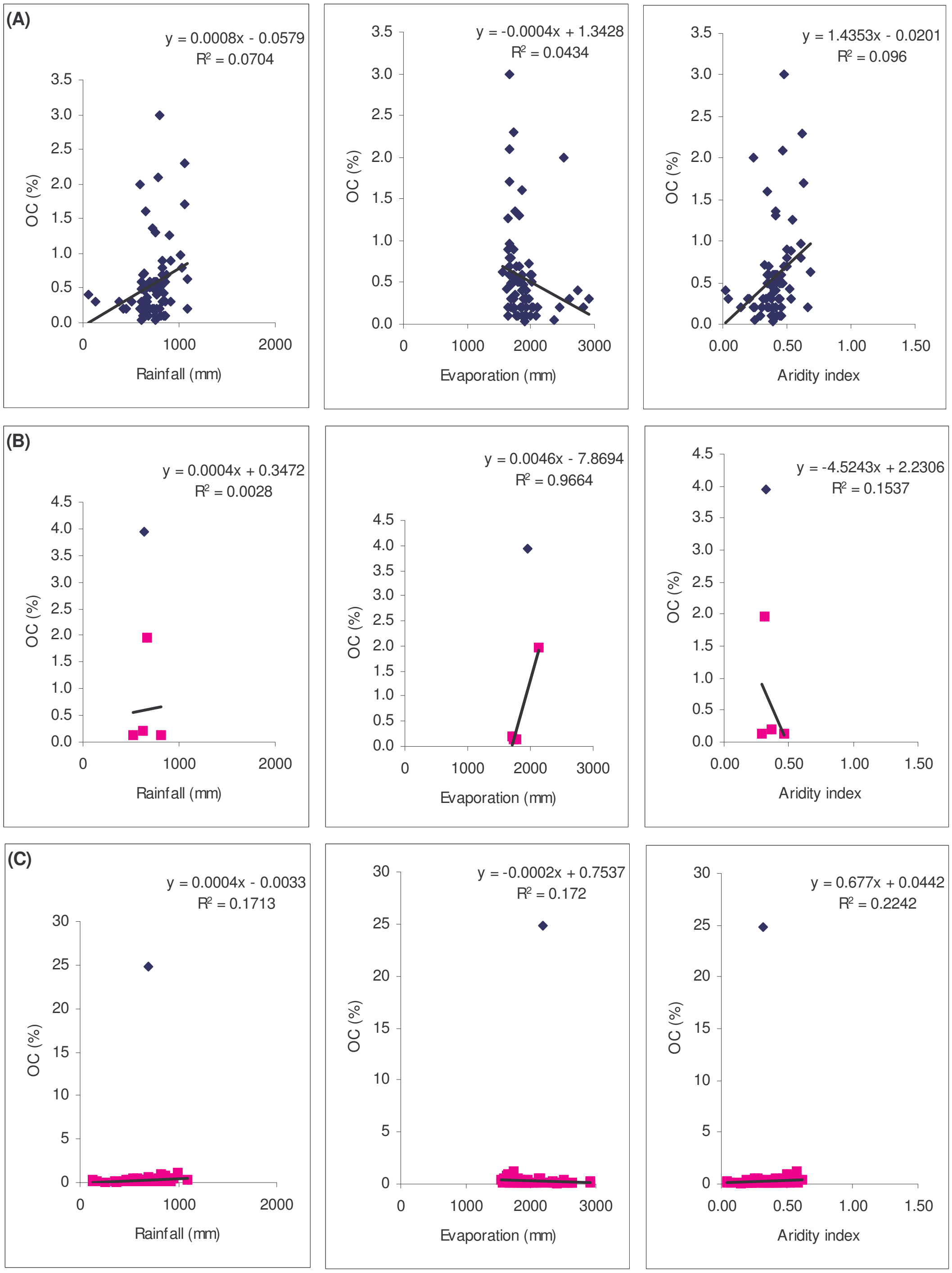


Figure 5.14 Relationship between soil organic carbon and the indices of climate in gley G horizon (A), unconsolidated material with signs of wetness (B), and unspecified materials with signs of wetness (C) horizons

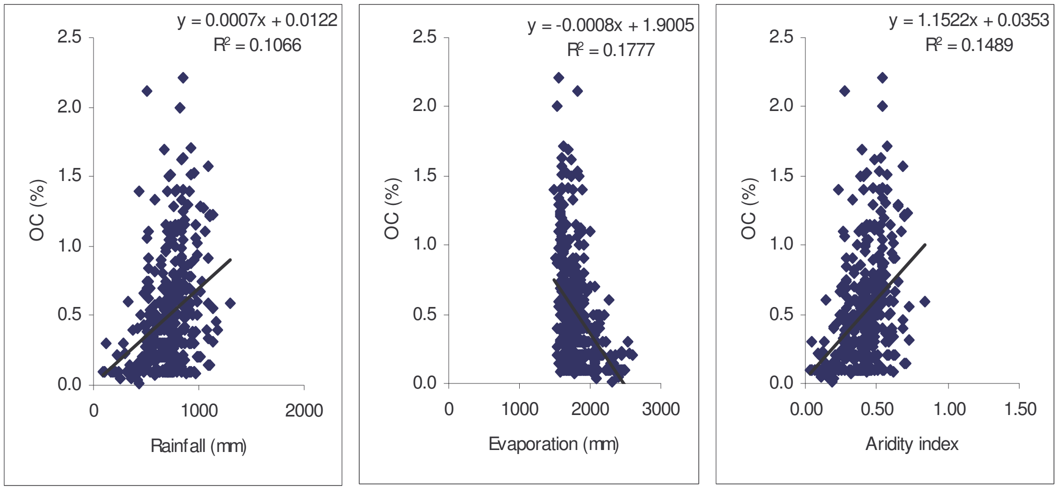


Figure 5.15 Relationship between soil organic carbon and the indices of climate in eluvial soils

5.3.1.14 Inceptic soils

Inceptic soils were divided into cumulic and lithic soils. The cumulic subgroup is made up of the neocutanic B, neocarbonate B, regic sand, and stratified alluvium (Figure 5.16).

High correlations were found between organic carbon content and climate in the neocarbonate B horizon (Figure 5.16). The correlation coefficient values were 0.54, 0.69 to 0.94 with rainfall, aridity index, and evaporation respectively. The number of observations of the neocarbonate B horizon (n = 9) probably helped to improve the correlation coefficient values. This horizon is one of the new additions that were included when the 1977 binomial system was amended to produce the 1991 taxonomic system (Laker, 2003). Although the neocarbonate B horizons are not the same as the soft carbonate horizons, the presence of calcium may have had a positive effect on organic carbon content. Carbonates have been reported to enhance the physical solidity of the soil (Le Roux *et al.,* 1999) which will help resist activities such as organic matter decomposition.

The neocarbonate B horizon develops in arid and semi-arid conditions (Soil Classification Working Group, 1991) and Figure 5.16 also revealed that these horizons were found in arid areas with and an average aridity index of 0.15 and low rainfall areas with an annual average of 375 mm. Low organic carbon values were found in this horizon because they are situated in arid areas which normally have high temperatures and therefore promote soil organic matter mineralization. The little organic carbon that was found there was probably because of the accumulation of carbonates associated with this horizon. The best correlation was found with evaporation, although negative, probably because a decrease in moisture content in the soil due to low precipitation produces conditions that are conducive for decomposition of organic matter resulting in low organic carbon values.

Only 27, 22, and 30% of variability in organic carbon was explained by rainfall, evaporation, and aridity index respectively in the neocutanic B horizon (Figure 5.16). Organic carbon also related positively with rainfall and aridity index whilst it was negative with evaporation. The neocutanic B horizon was also found in dry areas with an average aridity index of 0.27. This is probably why decomposition of organic matter is high as low soil water content promotes high microbial activity. Low water conditions provide the aerobic conditions needed for rapid mineralisation of organic matter (Havlin *et al.*, 1999).

Figure 5.17 illustrates the relationship between organic carbon and the climate indices in the remaining members of the cumulic subgroup of the inceptic soils. Low correlation coefficient values of 0.03 were found when organic carbon was correlated with rainfall, evaporation, and aridity index in the regic sand. The regic sand horizon is mainly made up of unconsolidated material which is usually aeolian (Soil Classification Working, Group, 1991). However, the correlation was positive with rainfall and aridity index, but was negative with evaporation. This horizon is characterised by very low organic carbon content (Table 5.4), therefore increased precipitation and decreased evaporation may influence organic carbon content positively in this horizon. These horizons were found in semi-arid areas with an average aridity index of 0.32.

The correlation coefficient values in the stratified alluvium horizon were slightly higher than in the regic sand, although still low for any conclusions to be drawn (Figure 5.17). Rainfall, evaporation, and aridity index were able to explain only 31%, 24%, and 31% variability of organic carbon in this horizon. Like all the other inceptic soils in the cumulic sub-group the relationship between organic carbon and rainfall as well as aridity index was positive and it was negative with evaporation in the stratified alluvium. These diagnostic horizons were found in semi-arid areas with an average aridity index of 0.31.

The lithic sub group is characterised by the lithocutanic B horizon and hard rock. These horizons are indicative of shallow soils (Laker, 2003). The correlation between organic carbon and the factors of climate: rainfall, evaporation, and aridity index was very low with correlation coefficient values of approximately 0.02 for each variable in the lithocutanic B and a range of 0.02 to 0.08 in the hard rock (Figure 5.18). The relationship between organic carbon and rainfall as well as aridity index was positive and was negative with evaporation in both the lithocutanic and hard rock. These horizons were found in arid to semi-arid climates.

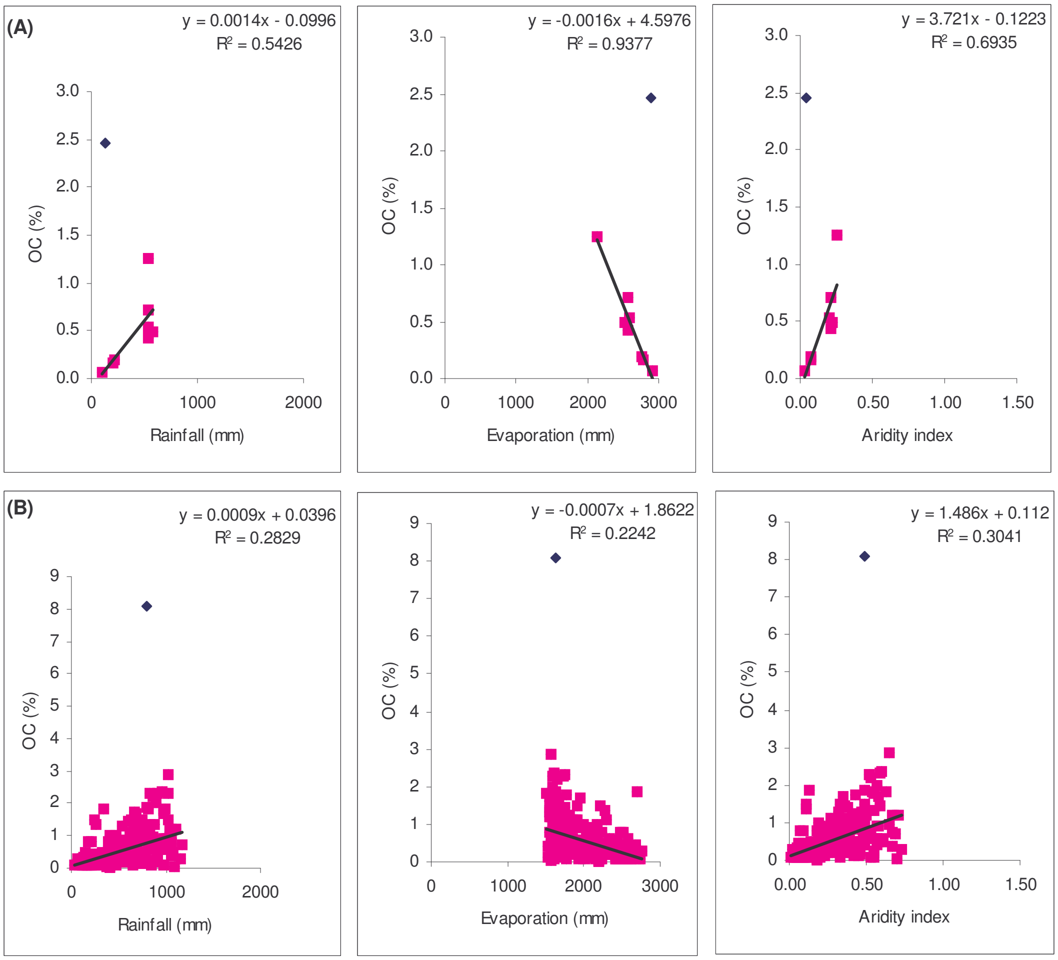


Figure 5.16 Relationship between soil organic carbon and the indices of climate in cumulic subgroup of inceptic soils: neocarbonate B (A) and neocutanic B (B) horizons

Organic carbon content related very poorly with rainfall, evaporation, and climate in the saprolite, unspecified dry material and unconsolidated material with signs of wetness horizons (Figure 5.19). The correlation coefficient values of the different variables ranged from 0.04 to 0.08. However, organic carbon related positively with rainfall and aridity index in the unconsolidated and unspecified dry materials and negatively with evaporation. These horizons behaved in the same manner probably because they are also made-up of diagnostic and non-diagnostic weathered material (Le Roux *et al.*, 1999). The time in which they are moist varies depending on the horizon. Their organic carbon content ranged from 0.27% to 0.33% which is very low (Table 5.4). These materials were found in semi-arid climates with an average aridity index of approximately 0.30.

However, the saprolite acted in a different manner from the unconsolidated and unspecified dry materials. Organic carbon content had a negative correlation with rainfall and aridity index while it was positive with evaporation (Figure 5.19). The saprolite is also made up of weathering rock so the organic carbon content in this horizon was expected to behave in the same way as the other dry materials.

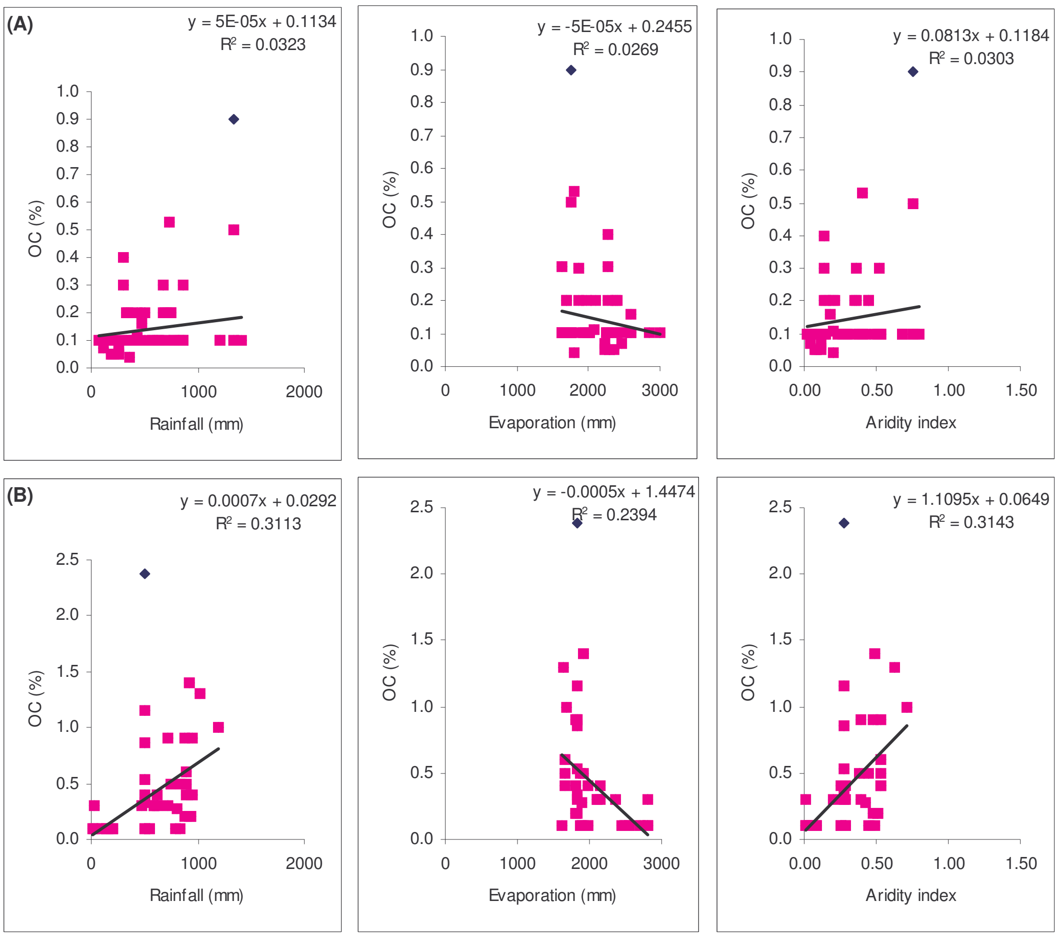


Figure 5.17 Relationship between soil organic carbon and the indices of climate in cumulic subgroup of inceptic soils: regic sand (A) and stratified alluvium (B)

The relationship between organic carbon content and the indices of climate namely: rainfall, evaporation, and aridity index was very poor for all the diagnostic topsoil horizons except with evaporation in the organic O horizon. The organic carbon content was positively related to rainfall and aridity index in the humic A, melanic A, vertic A, and orthic A horizons. It was negatively related to evaporation in the same horizons.

The opposite was experienced in the organic O horizon. Organic carbon was negatively related to rainfall and aridity index and it was positively related to evaporation. The diagnostic organic O horizon behaved in the same manner as the master O horizon (Chapter 4). Expectations were that because the formation of these horizons requires a high amount of water saturation, the organic carbon content would be higher as rainfall increased since there is less microbial activity meaning less decomposition thus leading to accumulation of organic carbon. Normally an increase in evaporation is associated with increased temperatures which mean increased microbial activity and mineralisation of organic carbon content. The optimum temperature for microbes to act on soil organic carbon is between 25 and 35ºC (Havlin *et al.*, 1999). However, the results revealed that as evaporation increased the organic carbon content also increased in the organic O horizon. The temperatures were therefore probably high enough to increase biomass production provided moisture content was adequate, but the temperatures were not suitable for the optimum activity of microbes.

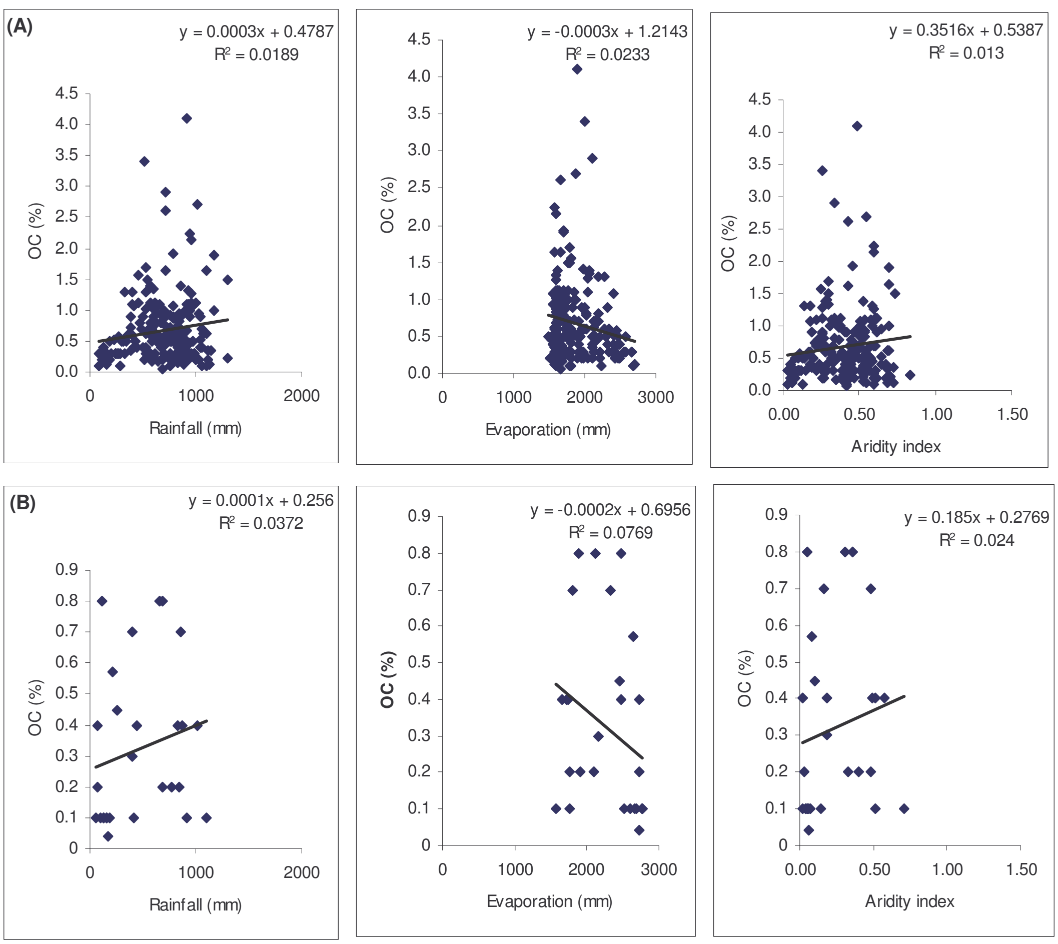


Figure 5.18 Relationship between soil organic carbon and the indices of climate in the lithic subgroup of the inceptic soils: lithocutanic B (A) and hard rock (B) horizons

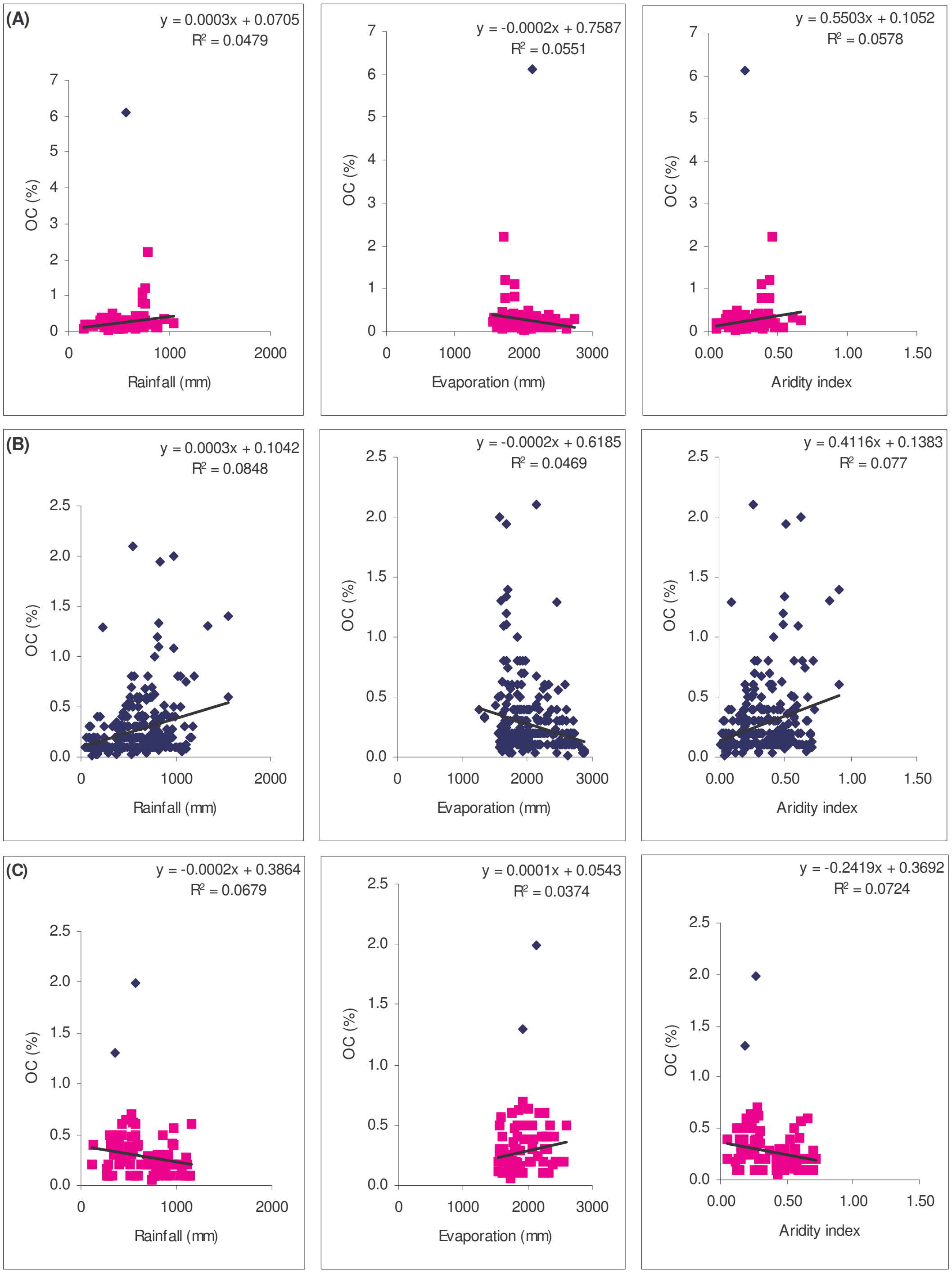


Figure 5.19 Relationship between soil organic carbon and the indices of climate in lithic sub group of the inceptic soils: unconsolidated material without signs of wetness (A), unspecified dry material (B), and saprolite (C) horizons

The correlation between organic carbon content and rainfall, evaporation, and aridity index in most diagnostic horizons and materials was poor except in the organic O (with evaporation), dorbank (silicic soils), soft carbonate B (calcic soils) and neocarbonate B (inceptic soils - cumulic group) horizons, which had very high correlation coefficient values. The high correlation coefficient values may have also been influenced by a low number of observations in the dorbank (n = 2), soft carbonate B (n = 3), and neocarbonate B (n = 9) horizons. These numbers of observations were very low when compared to the other diagnostic horizons.

Organic carbon content related negatively with rainfall and aridity index and positively with evaporation in the following diagnostic horizons: soft carbonate B, podzol B, hard plinthic B, saprolite, and the unconsolidated material with signs of wetness. However, evaporation seemed to have a positive effect on the organic carbon found in these horizons. A decrease in soil moisture up to certain levels coupled with proper crop and soil management strategies may help conserve soil organic carbon (Havlin *et al*., 1999).

In the other remaining horizons namely: humic A, melanic A, vertic A, orthic A, pedocutanic B, prismacutanic B, soft plinthic B, red apedal B, yellow-brown apedal B, red structured B, G, unspecified material with signs of wetness, E, neocarbonate B, neocutanic B, regic sand, stratified alluvium, lithocutanic B, hard rock, unconsolidated material without signs of wetness, unspecified dry material, and saprolite the organic carbon increased with an increase in the moisture content of the soil. These results correlated with the findings of several scientists. Alvarez & Lavado (1998), Hontoria *et al.* (1999), Jobbagy & Jackson (2000), and Dai & Huang (2006) all found that organic carbon content is positively correlated to rainfall. An increase in precipitation resulted in an increase in organic carbon content probably due to higher biomass production and less decomposition, mineralisation and microbial activity therefore leading to organic carbon accumulation. However, Spain (1990) reported a negative relationship between organic carbon and precipitation and argued that parent material and topography highly influence carbon levels.

Unfortunately, because of the low correlation coefficient values (with a few exceptions) that are dominating these results, the effect of rainfall, evaporation, and aridity index as factors of climate was not very conclusive. Probably the interaction of other factors such as parent material, temperature, vegetation, topography, and soil texture might improve the results.

5.3.2 Topography

Topography influences the formation of soils by affecting the type of vegetation, climate, vegetation, and drainage of soils in that vicinity (White, 2006). Buol *et al.* (1989) added that the characteristics of the land also affect organic activity, the rate of run-off and run-on processes as well as the sensitivity of the soil to wind and water erosion. Different microclimates which are a result of the changes caused by topography and drainage highly affect the conservation of soil organic matter (Carter, 1996). Topography encompasses the landscape features of an area which include slope aspect, slope percentage, slope shape, drainage, relief, and terrain morphology (Le Roux *et al.*, 1999). Therefore the effects of terrain morphological unit, slope percentage, slope type, and slope aspect on organic carbon content in diagnostic horizons and materials are dealt with here as described earlier.

5.3.2.1 Terrain morphological units

The crest, scarp, midslope, footslope, and valley bottom are the main terrain morphological units (Le Roux *et al.,* 1999). The midslopes and footslopes were further divided into upper and lower slopes. The average organic carbon contents were grouped per terrain unit. The relationship between organic carbon and terrain morphological units in the diagnostic horizons and materials is shown from Figures 5.20 to 5.25.

5.3.2.1.1 Organic soils

This soil group comprises of organic O horizons which have the highest organic carbon content of all diagnostic horizons. High accumulation of organic matter results from slow decomposition because of anaerobic conditions caused by prolonged saturation of the soil with water (White, 2006). The formation of this horizon in such conditions is supported by Figure 5.20 as diagnostic organic O horizons were reported only in the valley bottoms and footslopes. The Soil Classification Working Group (1991) stated that these horizons can be found in areas which can hold water for longer periods, *i.e.* in marshlands, swamps, and even on the slopes of mountains but not always. This means that the valley bottoms and footslopes provided the necessary conditions for the formation of organic O horizons since they have poor drainage and their water tables are high or closer to the soil surface (White, 2006). Mineralisation of organic matter is very slow under anaerobic and waterlogged conditions (Havlin *et al.*, 1999). The highest organic carbon content in the organic O was found at the valley bottom (21.4%) and the lowest at the footslope (18.3%). As expected the diagnostic organic O horizon behaved in the same way as the O master horizon (Section 4.3.2.1.1).

5.3.2.1.2 Humic soils

The humic A horizons are characterized by the buildup of humus which normally occurs in areas with a high rainfall and freely drained soils (Fey, 2009). However, aerobic conditions are required (Soil Classification Working Group, 1991). The highest average amount of organic carbon in the humic A horizons was recorded on the footslopes (9.14%) and the lowest on the lower midslopes (2.18%) as illustrated in Figure 5.20. The organic carbon content at the footslopes was significantly different from the amount found at the other slopes. Only one observation each of the humic A horizon was reported at the valley bottoms and lower footslopes. These areas are normally governed by anaerobic conditions since the water table is higher which shows that the formation of the humic A's under these conditions is very rare. The humic A horizon that was found there was probably formed when there was artificial drainage in those areas which decreased moisture content which would provide the aerobic conditions needed for humification of soil organic matter by microbes as well as earthworm activity (Le Roux *et al*., 1999).

No humic A horizons were found at the scarps. The humics are also formed in a plateau (Fey, 2009). Some (n = 23) were found on the well-drained crests. They were formed in their highest numbers at the midslopes (n = 34). The soils at the midslopes are deep and well-drained (Le Roux *et al*., 1999). Although not significant from the crest and upper midslopes, the organic carbon content in the midslopes was significantly higher than in the lower midslopes, probably due to poorer drainage conditions on the latter slopes.

5.3.2.1.3 Vertic soils

Vertic A horizons are distinguished by a high clay content and are situated in the lowest positions in the landscape (Fey, 2009). These horizons were found in increasing numbers at the lower midslopes, footslopes, midslopes, valley bottom, and lower footslopes (Figure 5.20). Vertic A horizons were also formed at the crests with an average organic carbon content of 1.40%. The highest organic carbon content in the vertic A horizons was observed on the lower footslopes (1.47%) and the lowest at the lower midslopes (0.73%). There was no significant difference in their organic carbon content on the lower footslopes, crests, and valley bottom. The midslopes had significantly higher organic carbon content than the lower midslopes. The highest number of observations of the vertic A horizons was found at the valley bottom (n = 29) and footslopes (n = 32). These lower lying areas of the landscape are governed by deposition of materials from upper slopes and have probably the best conditions for the formation of vertic A horizons.

5.3.2.1.4 Melanic soils

On average, the highest organic carbon content in the melanic A horizons was measured on the upper midslopes (3.60%) and the lowest at the valley bottoms (1.21%) as shown in Figure 5.20. The organic carbon content at the valley bottoms was not significantly different from the footslopes. These are areas that have poor drainage and the melanic A horizons that are found here were not expected to have a low organic carbon content. This is because organic matter decomposition tends to be slower in poorly drained areas since microbial activity is slow (Havlin *et al*., 1999). The conditions that affect the organic carbon of the melanic A horizons positively were found on the upper midslopes. Soils on the midslopes are normally deep with a good drainage system (Le Roux *et al*., 1999). These results correspond with the findings of Moges and Holden (2008) who reported higher organic carbon contents on the midslopes than on the lower slopes. They reasoned that this occurred because of increased sand deposition that has occurred at the lower slopes. The crests also had melanic A horizons that have a high organic carbon content although it was not significantly different from the midslopes and lower midslopes.

Van der Merwe *et al.* (2002) stated that melanic soils were not limited to certain positions on the landscape. They found that most of the melanic soils were formed on the midslopes (32%), followed by valleybottoms (30%), crests (22%), and footslopes (16%). Their results correlated with the findings of this study because highest numbers of melanic A horizons were formed on the midslopes (n = 55). There were no melanic A horizons at the scarps. This proves that melanic A horizons are mainly found on gentle slopes of level areas (Van der Merwe *et al*., 2002).

5.3.2.1.5 Orthic soils

The orthic A horizon is the most common diagnostic topsoil in South Africa as shown in Table 5.4 (n = 5459). This horizon was found in all positions of the landscape (Figure 5.20). The orthic A has been known to occur over a wide array of soil forming circumstances therefore they will differ in properties such as organic carbon content and texture (Soil Classification Working Group, 1991). In the orthic A horizons on average, the highest organic carbon content was found on the upper midslopes (1.89%) and the lowest was surprisingly at the lower midslopes (0.25%). This shows that there is no particular pattern on which conditions are suitable for the accumulation of organic carbon in the orthic A. The accumulation of organic carbon in these horizons probably depends not only on the terrain of the area but also on the interaction of conditions such as land management, vegetation type, and climate (Carter, 1996).

Any topsoil that does not show the characteristics of the organic O, melanic A, humic A, and vertic A horizons can be classified as an orthic A horizon (Soil Classification Working Group, 1991). However, the highest number of observations of the orthic A horizons were found on the midslopes (n = 619), followed by the footslopes at (n = 457), crest (n = 233), and the valley bottom (n = 181). At least these statistics reveal that they are mostly formed at the midslopes where soils are deep and well-drained but are prone to surface erosion. The drainage of the orthic A horizons decreases from the footslopes to the valley bottom. Very few orthic A horizons were found at the other terrain morphological units, especially the pan (n = 3) and scarps (n = 2).

5.3.2.1.6 Silicic soils

The main feature of the silicic soils is the presence of the dorbank B horizon (Fey, 2009). This horizon was found on the footslopes and midslopes only (Figure 5.21). On average, highest organic carbon content was recorded at the midslopes (0.20%) and the lowest at the footslopes (0.10%). The dorbank is usually associated with dry areas (Laker, 2003). However, the dorbank B horizon was observed at the footslopes which normally contain soils that have some signs of wetness.

5.3.2.1.7 Calcic soils

The soft carbonate B horizons were found on the midslopes, crest and upper midslopes (Figure 5.21). On average, organic carbon content was highest at the upper midslopes (0.69%) followed by the crests (0.63%), and the lowest at the midslopes (0.10%). Only three observations of the horizon were made therefore their significance in organic carbon content cannot be made.

5.3.2.1.8 Duplex soils

The duplex soils are normally associated with the accumulation of clay either by illuviation or by eluviation from the overlying horizons or from the higher slopes (Fey, 2009). Clay is known for its effect of shielding organic compounds from any instability such as decomposition (Burke *et al.*, 1989). The highest average organic carbon content in the pedocutanic B and prismacutanic B horizons was recorded at the upper midslopes (1.19% and 0.67%) respectively (Figure 5.21). It was most likely removed with clay from the horizons in the upper slopes by illuviation and deposited in the upper footslopes and midslopes. The organic carbon content in those slopes was not significantly different in both horizons. The lowest average organic carbon content was measured at the lower footslopes for the pedocutanic B (0.47%) and at the lower midslopes for the prismacutanic B horizons (0.31%).

Moges and Holden (2008) reported that organic carbon and clay content followed a similar pattern on the landscape. They reported that the midslopes had a significantly higher clay and organic carbon content than the lower slopes. This indicates that clay does have a way of protecting organic carbon from depletion.

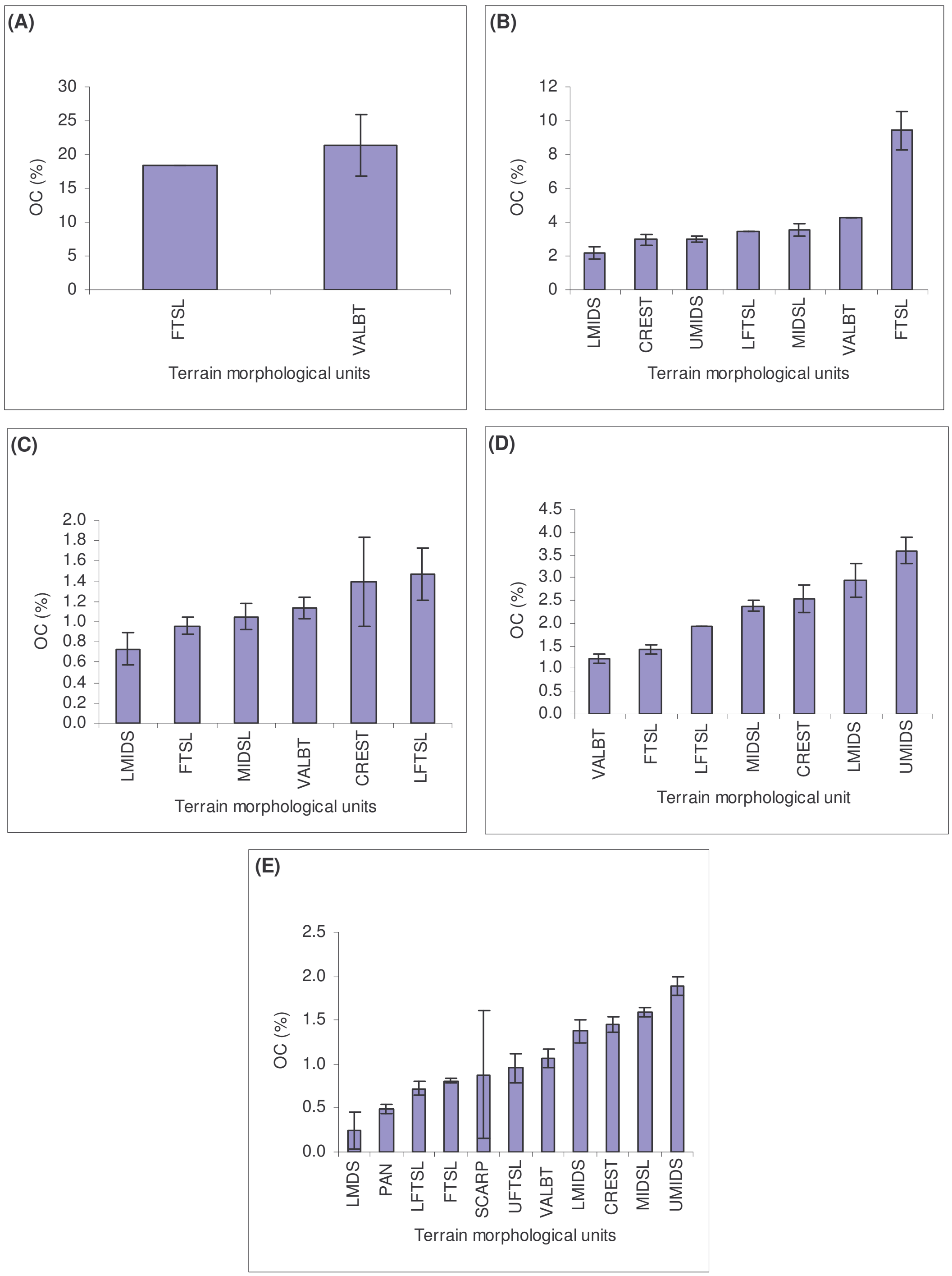


Figure 5.20 Effect of terrain morphological units on the diagnostic topsoil horizons: organic O (A), humic A (B), vertic A (C), melanic A (D), and orthic A (ot)

There was no significant difference in organic carbon content at the crest and midslopes in both subsoils. Both subsoils also showed no significant difference in organic carbon content at the valley bottoms, lower footslopes, and footslopes. Most of these horizons were found at the footslopes and midslopes. Fey (2009) stated that soils with a prismacutanic B horizon are normally found on lower and gentle slopes. Due to a high content of clay associated with duplex soils their properties such as drainage, erodibility which is usually high (Fey, 2009) and fertility highly depend on the topographic positions of these soils in the landscape. Most pedocutanic B horizons were found on the footslopes (n = 119) and the midslopes (n = 122) while the prismacutanic B horizons were mostly formed on the footslopes (n = 87).

5.3.2.1.9 Podzolic soils

The podzol B horizons were found at the crest, midslopes, and footslopes (Figure 5.21). On average the highest organic carbon content, although not significantly different from the organic carbon content at the midslopes, was measured at the footslopes (1.59%). The lowest organic carbon was recorded on the crests (0.10%). No podzols were found at the scarp and valley bottom. Depending on the type of podzol, some are usually found upslope and have free drainage, whereas some can be found at the lower slopes and are referred to as hydromorphic podzols (Fey, 2009). From the land type survey data it was obvious that podzols occur upslope at the crests (n = 10) and lower slopes at the footslopes (n = 6), the highest numbers were found at the midslopes (n = 12). The podzols reported at the footslopes are hydromorphic, which are probably why they had the highest organic carbon content. Even though the accumulation of undecomposed organic matter in the podzols requires aerobic conditions (Fey, 2009) the presence of moisture in hydromorphic soils may help increase biomass production thus contributing to increased organic material.

5.3.2.1.10 Plinthic soils

As shown in Figure 5.22, the highest organic carbon content in the plinthic soils was reported on the upper footslopes in the soft plinthic B (0.56%) and hard plinthic B (0.45%) horizons. The lowest organic carbon content was found on the lower midslopes (0.09%) in the soft plinthic B and on the crest (0.10%) in the hard plinthic B. The soft plinthic B horizons were found in more areas in the landscape than the hard plinthic B horizons. There were no hard plinthic B horizons at the valley bottom. Both plinthic B horizons were expected at the valley bottom because their most domineering characteristics are that they are associated with fluctuating water tables and periodical saturation (Soil Classification Working Group, 1991). The difference between them is a result of soil forming factors such as time and iron content of the parent material (Le Roux *et al.,* 1999). There were also no hard plinthic B horizons at the lower midslopes, and upper footslopes.

The standard error bars revealed a lot of variation in organic carbon content at the lower footslopes in both plinthic B horizons. There was no significant difference in organic carbon content in soft plinthic B horizons from the upper footslopes, midslopes, and lower footslopes. The midslopes (n = 70) and footslopes (n = 59) proved to have the most suitable conditions for the formation of the soft plinthic B horizons as most observations were observed in those parts of the landscape. Most hard plinthic B horizons were formed at the footslopes (n = 3).

Soils at the footslopes are normally poorly drained and have signs of wetness due to raised water tables (White, 2006). This is probably why a high number of plinthic B horizons were found at the footslopes. The midslopes probably offered suitable conditions for the formation of the soft plinthic B horizons because of the presence of an impermeable underlying layer which may hold water or because of the deposition of iron from upland eroding slopes.

5.3.2.1.11 Oxidic soils

On average, the highest organic carbon content in the oxidic soils was found on the upper footslopes (0.69%) in the red apedal B, and the upper midslopes (1.08%) in the red structured B horizons (Figure 5.22). The yellow-brown apedal B horizons were reported at the valley bottom with an average organic carbon content of 0.54%. The lowest average organic carbon content was on the footslopes (0.37%) and valley bottoms (0.45%) for the red apedal and red structured B horizons respectively.

There were no oxidic soils at the scarps which are normally very steep and with a high rate of physical weathering and erosion leading to shallow soils. Perhaps that is the reason why there are no oxidic soils at the scarps. The organic carbon content at the upper footslopes was not significantly different from the organic carbon content at the midslopes, lower midslopes, crests, valley bottom, upper midslopes, and lower footslopes for the red apedal B horizons. In these horizons, organic carbon content at the upper midslopes, midslopes, and crests was also not significantly different from each other. Likewise the red structured B horizons at the valley bottom, footslopes, and lower midslopes have similar organic carbon contents. Most red apedal B horizons (n = 268) and red structured B horizons (n = 55) were formed at the midslopes. According to Fey (2009) in these soils, oxides of iron build up through weathering and also require well-drained and aerated conditions which give the red colour to these soils. This is proven by the concentration of these soils at the midslopes as they are able to offer the most suitable conditions for their formation, namely having good drainage.

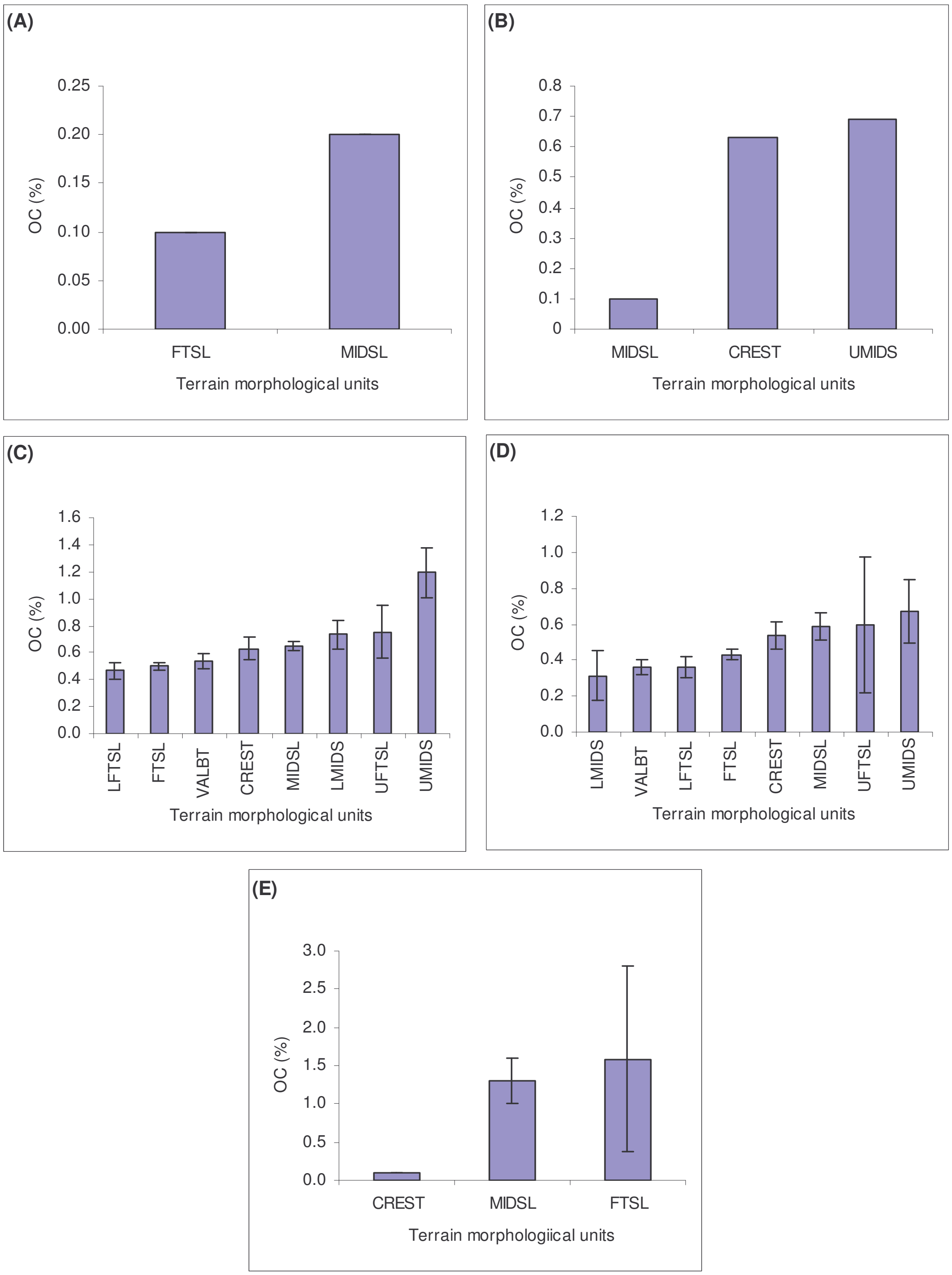


Figure 5.21 Effect of terrain morphological units on soil organic carbon in the silicic: dorbank B (A), calcic: soft carbonate (B), duplex: pedocutanic B (C) and prismacutanic B (D), and podzolic soils: podzol B (E)

5.3.2.1.12 Gley soils

The highest average organic carbon content was found at the valley bottom for the G horizon (0.65%), unconsolidated (0.25%), and unspecified materials (3.44%) as shown in Figure 5.23. Soils at the valley bottom usually have alluvial characteristics and the anaerobic conditions caused by prolonged water saturation associated with this part of the landscape favours the accumulation of organic carbon. However, the gleycutanic B horizons behaved differently as the highest average organic carbon content was recorded at the upper footslopes (0.58%). The lowest average organic carbon content was measured at the lower footslopes in the unspecified material (0.02%) and the gleycutanic B horizon (0.19%). The G horizons at the upper footslopes (0.04%) and the unconsolidated material at the footslopes (0.14%) contained the lowest average organic carbon. No gley soils were found at the scarps. Amongst all the gley soils the unspecified material with signs of wetness recorded the highest organic carbon content. This is probably because of a slower decomposition rate because of the high moisture content associated with the unspecified material with signs of wetness.

Most of the G horizons were found at the valley bottom (n = 34). The valley bottom offered the appropriate conditions for the formation of these horizons as they are formed under prolonged water saturation except when drained by artificial or natural ways (Soil Classification Working Group, 1991). Soils at the valley bottom are in many instances poorly drained (Le Roux *et al.*, 1999). Such poorly drained conditions favoured the higher organic carbon found in unconsolidated and unspecified materials which are also linked to prolonged periods of saturation with water.

In the G horizon organic carbon content at the midslopes was significantly lower than on the footslopes and valley bottoms, whereas the organic carbon content of this horizon on the footslopes was not significantly different from that on the valley bottoms. There was no significant difference in organic carbon content in all parts of the landscape where the gleycutanic B horizons were found. The difference in organic carbon content of the unconsolidated materials with signs of wetness on the footslopes and valley bottoms was also not significantly different. The organic carbon content in the valley bottom was significantly higher than on all parts of the landscape where the unspecified material with signs of wetness was found.

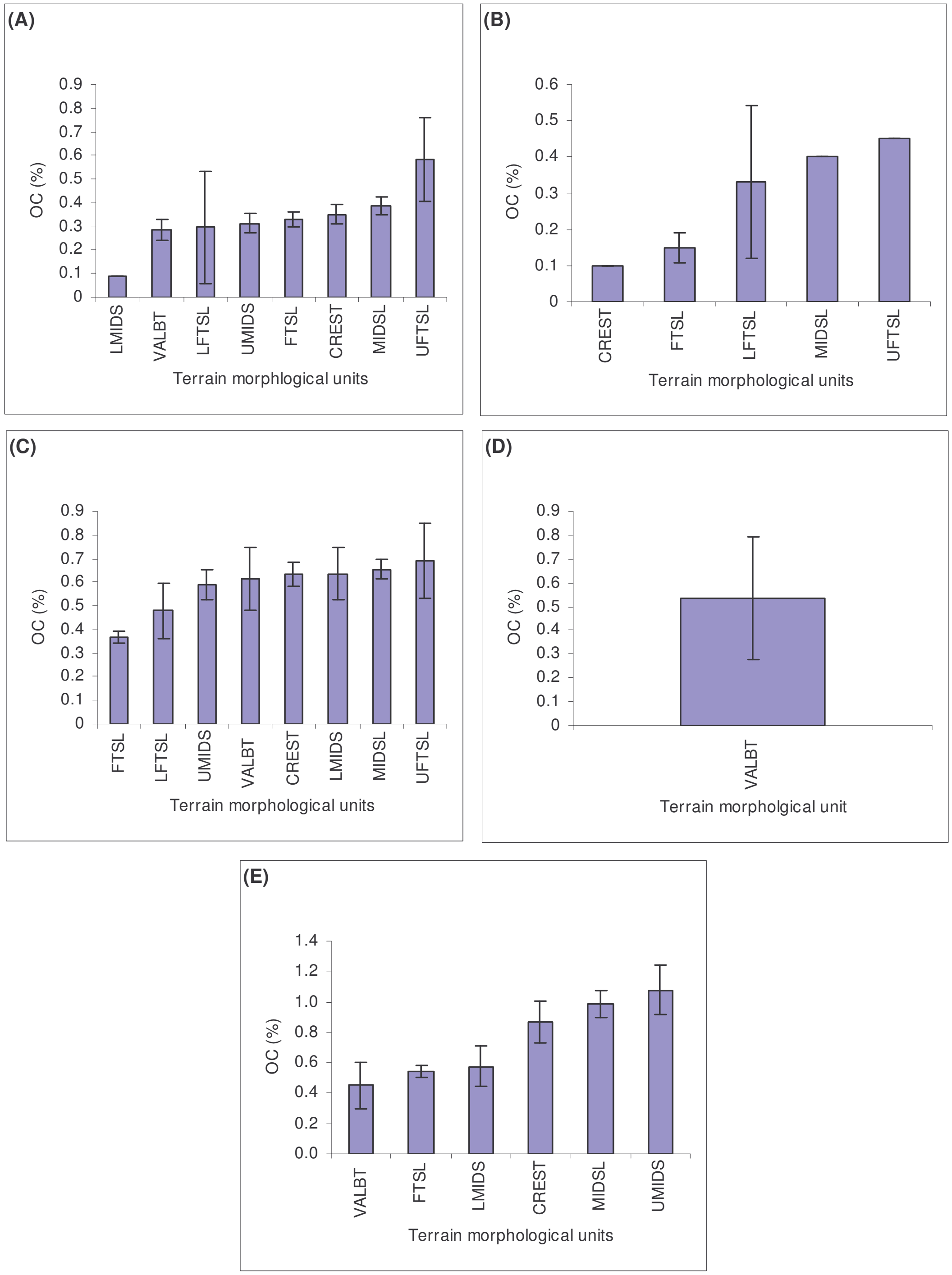


Figure 5.22 Effect of terrain morphological units on soil organic carbon in the plinthic soils: soft plinthic B (A), hard plinthic B (B), and oxidic soils: red apedal B (C), yellow-brown apedal B (D), and red structured B (E) horizons.

5.3.2.1.13 Eluvial soils

On average, the highest organic carbon content in the E horizons was on the upper midslopes (0.93%) and the lowest on the upper footslopes (0.28%) as illustrated in Figure 5.23. The average organic carbon content in E horizons at the upper midslopes was significantly higher than those found at the other parts of the landscapes. No E horizons were reported at the scarps.

Most of the E horizons were situated at the midslopes (n = 86). This is probably because the formation of E horizons requires conditions where eluviation and reduction can occur (White, 2006). Thus it seems that the process of eluviation of clay, humus, oxide minerals that takes place in this horizon is highly favoured by the conditions at the midslopes.

5.3.2.1.14 Inceptic soils

Inceptic soils were divided into the cumulic and lithic subgroups. The cumulic subgroup is made up of the neocutanic B, neocarbonate B, regic sand, and stratified alluvium. The lithic subgroup comprises lithocutanic B, hard rock, saprolite, unconsolidated dry material, and unspecified dry material.

The neocutanic B horizon was found at most areas of the landscape (Figure 5.24). In this horizon the highest organic carbon content was recorded on the scarp (1.10%) but unfortunately only one observation was made. The crests proved also to have a higher organic carbon content of 0.78% even though it was not significantly different from the organic carbon content on the upper midslopes, midslopes, lower midslopes, valley bottoms, and footslopes. The organic carbon content on the footslopes, lower footslopes and upper footslopes as well as the pans was not different significantly. The lowest organic carbon content was recorded at the pan (0.29%). This may probably be because of less plant production due to the saline conditions found on the pan (White, 2006). The neocutanic B horizon is normally associated with young soils usually from alluvial or colluvial deposits (Fey, 2009).

The Soil Classification Working Group (1991) states that neocutanics are formed from either alluvial or colluvial materials and are mostly found at lower lying slopes. According to the results of this study, the highest observations of this horizon were indeed reported at the footslopes (n = 84) and valley bottoms (n = 72).

The neocarbonate B horizons (n = 5) were found at the footslopes, midslopes, and valley bottoms (Figure 5.24). Their highest organic carbon content was recorded at the valley bottoms (2.46%) and the lowest at the footslopes (0.07%). The neocarbonate B horizon was one of the newest diagnostic horizons that were added during the development of the Taxonomic Soil Classification System for South Africa (Laker, 2003). Since the land type survey cuts across the old binomial system and the new taxonomic system that is probably why there are only a few observations recorded of the neocarbonate B horizon. In the old system they were classified as the calcareous red or yellow-brown apedal B or neocutanic B horizons (Laker, 2003).

The regic sand was found on the valley bottoms, footslopes, crests, and midslopes (Figure 5.24). On average, the highest organic carbon content of 0.28% was found at the midslopes and the lowest of 0.10% at the valley bottoms. The organic carbon content at the valley bottoms was expected to be higher than the amount found at the other parts of the landscape as the wet conditions found in this area would allow for the accumulation of organic matter. Sometimes the depositional areas receive coarse sediment from the eroding areas on the upper slopes. Moges & Holden (2008) reported lower organic carbon contents on the depositional areas when compared to the upper slopes. FitzPatrick (1983) states that the presence of a good vegetation cover on the upper slopes can result in the formation of soils rich in nutrients on the upper slopes. This is probably why the highest organic carbon content was found at the midslopes.

The stratified alluvium horizons were restricted to the valley bottoms and footslopes only (Figure 5.24). In these horizons the highest organic carbon content was observed on the footslopes (0.78%) and the lowest at the valley bottom (0.30%). The formation of these kind of horizons is usually from depositional processes (Soil Classification Working Group, 1991). That is probably why most of these horizons occur at the valley bottom (n = 12), where most alluvial and colluvial deposits are found. The organic carbon content on the footslopes was significantly higher than at the valley bottoms.

The organic carbon content in the lithocutanic B horizons increased from the valley bottoms (0.20%) to the lower midslopes (0.77%) as illustrated in Figure 5.25. At both the upper or lower midslopes organic carbon content seemed to be the highest. However, it was not significantly higher than at the other parts of the landscape. The lithocutanic B horizon is normally associated with young landscapes and shallow soils that show signs of partial weathering (Fey, 2009). Most of these horizons were found at the midslopes.

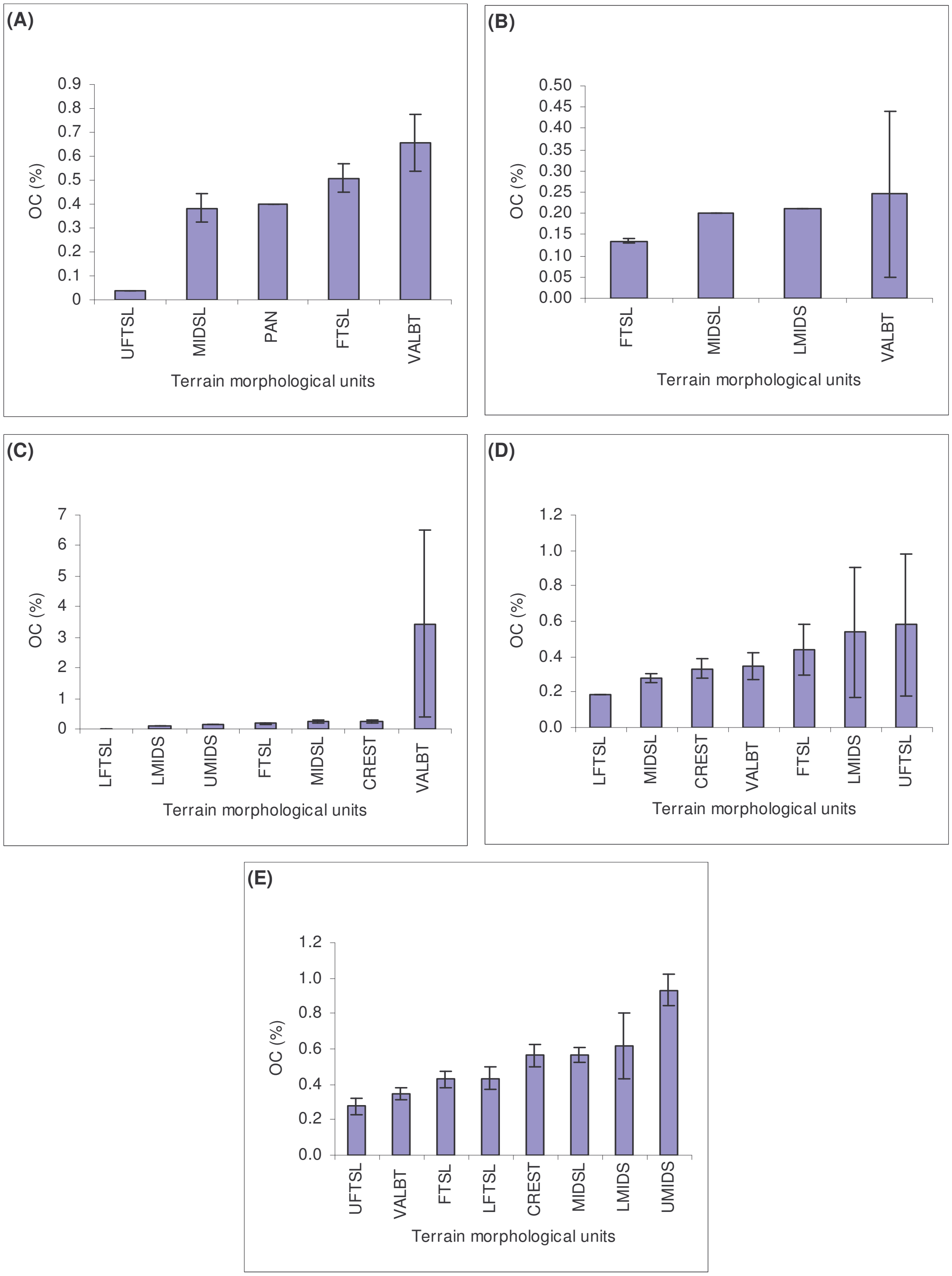


Figure 5.23 Effect of terrain morphological units on soil organic carbon in the gley soils: G horizon (A), unconsolidated material with signs of wetness (B), unspecified material with signs of wetness (C), and gleycutanic B (D), and eluvial soils: E horizons (E)

Hard rock is also a sign of shallow soils (Soil Classification Working Group, 1991) found on the valley bottoms, midslopes, footslopes, pan, and crests (Figure 5.25). Even though hard rocks are characterised by low organic carbon the highest content of 0.57% was found on the crests. Similar to the lithocutanic B horizon, lowest organic carbon content of 0.07% was found at the valley bottoms, probably because it is too hard for any penetration either by roots or water and therefore no build-up of organic matter can occur in these horizons.

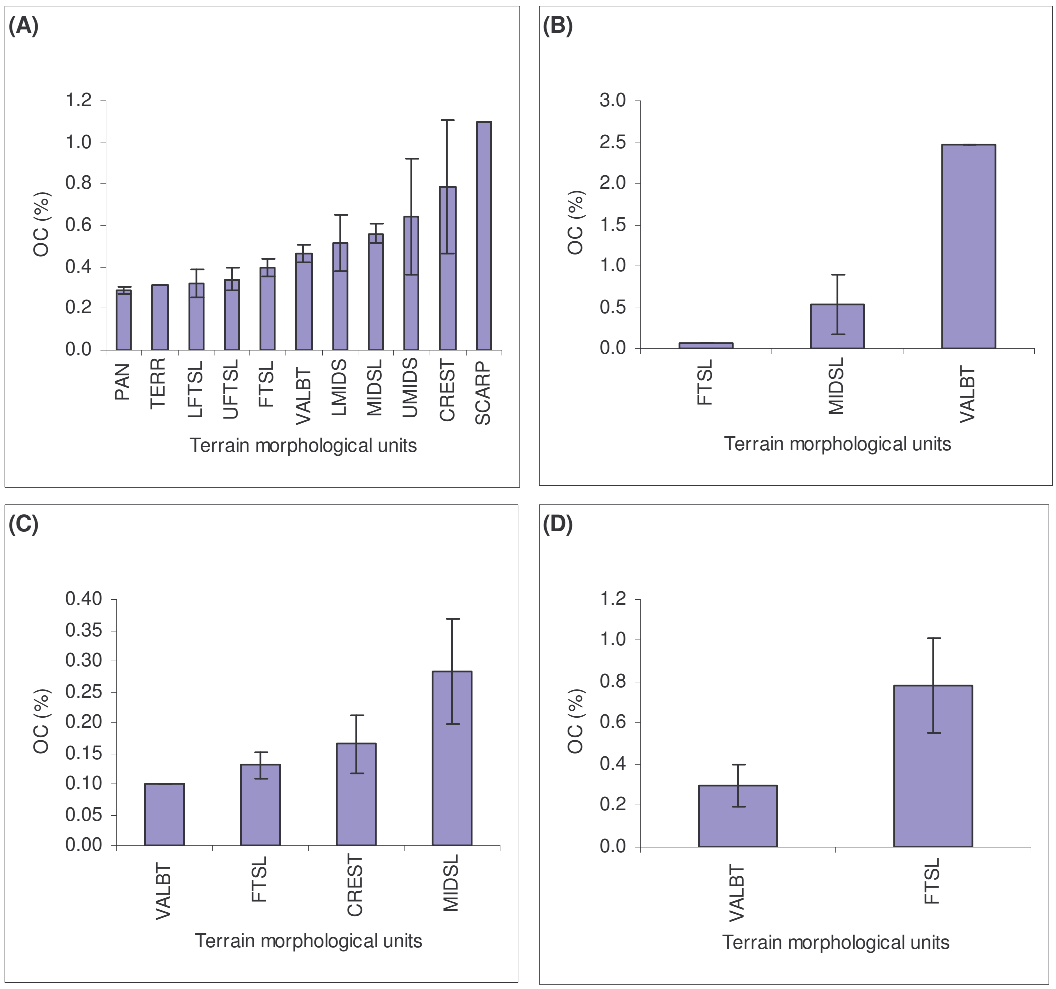


Figure 5.24 Effect of terrain morphological units on soil organic carbon in the cumulic sub-group of the inceptic soils: neocutanic B (A), neocarbonate B (B), regic sand (C), and stratified alluvium (D)

Unconsolidated and unspecified materials were found at different parts of the landscape (Figure 5.25), but not on scarps. The highest organic carbon content was recorded on the footslopes (0.38%) for the unconsolidated material without signs of wetness and scarps (0.60%) for the unspecified dry materials whereas the lowest was on the crest (0.10%) for the unconsolidated material without signs of wetness and upper midslopes (0.09%) for the unspecified dry materials. According to the Soil Classification Working Group (1991) the unconsolidated material without signs of wetness can normally be found in soils at the lower slopes or in areas where deposition is high. The land type survey data also revealed that most observations of soils with an unconsolidated dry underlying material occur at the footslopes (n = 33). A very low number of observations were made at the crests where there are no depositional conditions. Soils with a layer of unspecified material without signs of wetness were mostly found at the midslopes (n = 63).

There was no significant difference between the organic carbon content at all parts of the landscape where the unconsolidated material without signs of wetness was found (Figure 5.25). The organic carbon content in the unspecified dry material on the midslopes was significantly higher than at the crests, lower midslopes, lower footslopes, and upper midslopes. There was no significant difference in organic carbon content on the valley bottoms, footslopes, and midslopes.

Saprolite is a horizon made up of weathering rock (Soil Classification Working Group, 1991). These horizons on the footslopes had the highest organic carbon content (0.49%) as shown in Figure 5.25. The lowest organic carbon content was found on the upper footslopes (0.17%). The organic carbon content on any of the midslopes was not significantly different.

Even though South African soils have very low organic carbon contents the different terrain morphological units have shown an impact on this parameter. The highest organic carbon content was found in organic O horizons at the footslopes (21.4%). These results correlate with the results of Wang *et al.* (2008) who reported that organic carbon was higher in the lower lying areas that are dominated by deposition when compared to the upper slopes where erosion is high. They reasoned that the eroded material carried by wind or water tends to help redistribute organic carbon to the lower areas. Soils at the footslopes have poor drainage and have higher watertables (White, 2006). These anaerobic conditions help to slow down the decomposition of organic matter (Havlin *et al*., 1999). Increased plant production resulting from high moisture content also helps in adding soil organic matter (Carter, 1996). The lowest organic carbon content varied depending on the properties of the particular diagnostic horizon as well as its position on the landscape.

Depending on the diagnostic horizon, some of them are limited to a certain area in the landscape. For example the yellow-brown apedal B horizons were restricted to the valley bottom only since a very moist soil regime is required for the formation of a soil that is yellow in colour (Soil Classification Working Group, 1991). A certain pattern was also observed in some soils that are in the same group. The gley soils with diagnostic horizons and materials that have signs of wetness *e.g.* G horizon, unconsolidated material with signs of wetness, and unspecified material with signs of wetness were mostly found at lower parts of the landscape such as the valley bottom and footslopes.

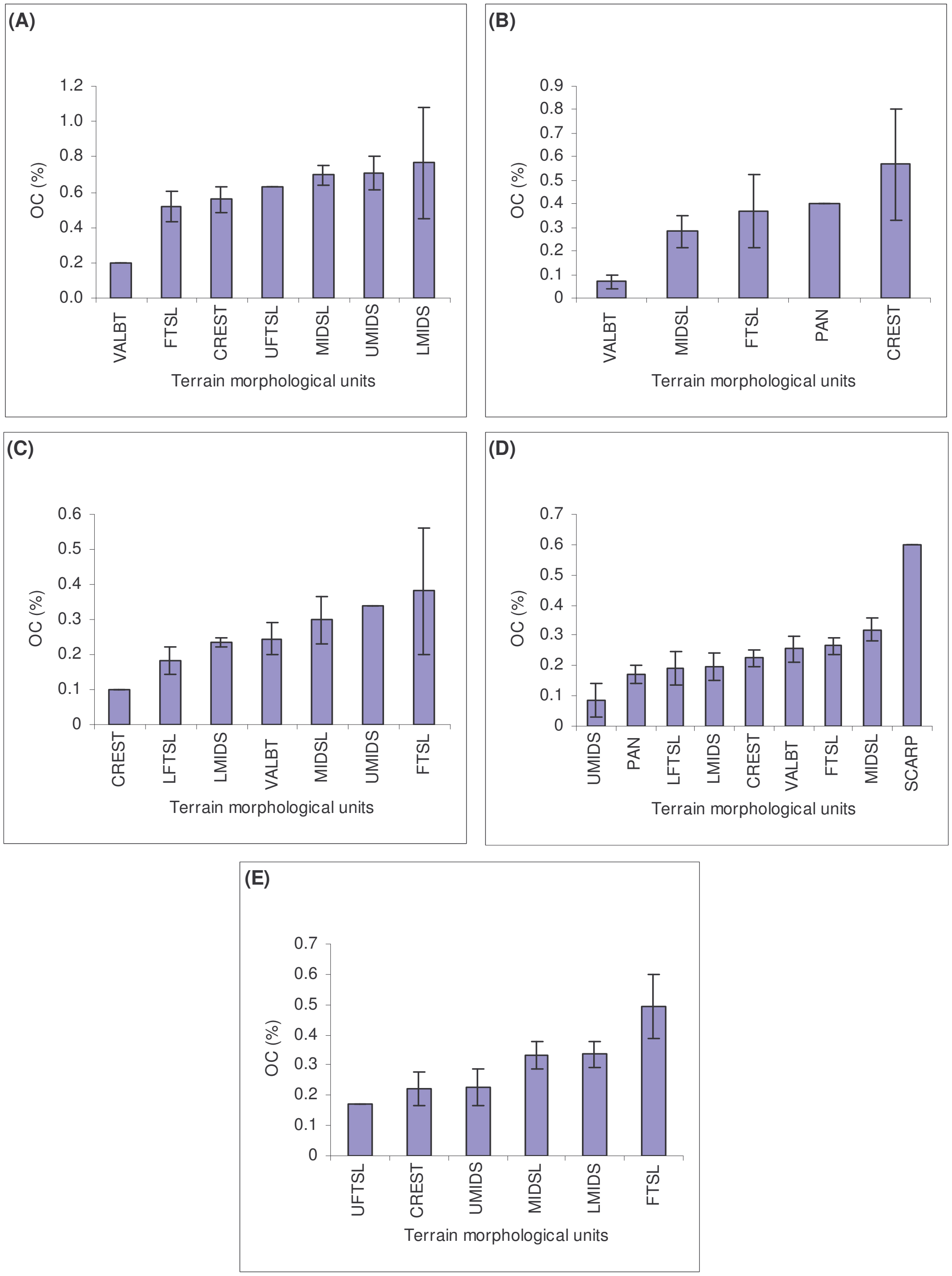


Figure 5.25 Effect of terrain morphological units on soil organic carbon in the lithic subgroup of the inceptic soils: lithocutanic B (A), rock (B), unconsolidated material without signs of wetness (C), unspecified dry material (D), and saprolite (E)

The highest organic carbon content in these horizons was noted in soils that are situated at the valley bottoms where alluvial and anaerobic conditions prevail thus promoting the accumulation of organic carbon by also hindering microbial activity. Anaerobic conditions help to slow down organic carbon decomposition (Havlin *et al*., 1999).

The highest organic carbon content in the plinthic B horizons was recorded in soils found at the upper footslopes. Soils at the upper footslopes are not very well-drained and because of a fluctuating water table, these soils show signs of wetness. Most soils with the prominent diagnostic horizons were observed at the footslopes and midslopes. Unfortunately, no particular pattern was picked up in some members of the different soil groups. Not many diagnostic horizons were recorded at the scarps.

Therefore the different conditions that are found in different parts of the landscape highly influence the types of soils found. The gley soils occur mostly at the valley bottom, most oxidic soils were found at the midslopes, and plinthic soils at the footslopes and midslopes. The lithic subgroup of the inceptic soils was mostly observed at the midslopes except the unconsolidated dry material which was found at the footslopes. There was no particular pattern on where the diagnostic horizons of the soils in the cumulic subgroup were formed. The eluvial soils were formed mostly on the midslopes where well-drained soils are found. Suitable conditions for the eluviation of clay, humus, and oxide minerals leading to the formation of an E horizon are highly promoted on the midslopes. The diagnostic horizons for the duplex soils were mostly formed at the footslopes which allow for the illuviation of clay as the soils in these areas are not very well-drained. Both the calcic and silicic soils were not very common in the land type survey data therefore not much can be learned in relation to their formation in different parts of the landscape.

5.3.2.2 Slope percentage

The gradient of the slopes highly influences the efficiency of water in soil by controlling the amount of water lost as well as the amount of water which the soil can hold (White, 2006). Fitzpatrick (1983) stated that the danger of soil erosion increases as the gradient of slopes increases. After dividing their samples into two slope groups, namely a lower slope class (0 - 3º) and higher slope class (>3º), Wang *et al*. (2008) reported significantly higher organic carbon levels in the lower slope class than in the higher slope class. Using the land type survey data the effects of slope percentage on organic carbon in the diagnostic horizons are dealt with in this section.

5.3.2.2.1 Organic soils

Soils with organic O horizons occur at slopes of <3% (Figure 5.26). The highest organic carbon content (24.43% C) in these horizons was recorded at 1% slopes which are basically level. The lowest organic carbon content (9.36% C) was reported in organic O horizons situated at 3% slopes. Organic O horizons are formed only in soils on slopes that allow large accumulations of organic material due to prolonged saturation periods with water (Soil Classification Working Group, 1991). The master O horizon (Section 4.3.2.2.1) was also formed under similar slopes as the diagnostic organic O horizon, namely 1 to 2%. Soils found at the lower slopes tend to have high water tables and poor drainage (White, 2006). This is probably why these soils allow for the formation of organic O horizons.

5.3.2.2.2 Humic soils

Humic A horizons were found on slopes ranging from 1 to 35% (Figure 5.26). The humic A horizons with the highest organic carbon content occur at 8% slopes (7.89% C) and 35% slopes (6.57% C). Soils on these slopes probably provided the free drainage and aerobic conditions needed for the accumulation of humified organic matter that is characteristic of this topsoil. The lowest organic carbon content in the humic A horizons (1.70% C) was measured in soils at 7% slopes. The highest number of humic A horizons were noted at 2% slopes (n = 18). Generally, the number of humic A topsoils decreased when slope percentage increased, up to the highest slope of 35% where only three occurrences were found. There was no significant difference in organic carbon between humic A horizons found at 1% and 35% slopes.

5.3.2.2.3 Vertic soils

The vertic topsoils were found within a slope ranging from 0 to 10% (Figure 5.26). In these topsoils the highest organic carbon content (2.70% C) was recorded at slopes of 0% whilst the lowest (0.75% C) was at 6% slopes. The organic carbon content of vertic A horizons decreased as the slope percentage increased except at 7% slope where the organic carbon content was 1.80% C. These horizons have a high water holding capacity due to high clay content (Soil Classification Working Group, 1991). Therefore a combination of a vertic A horizon with a poorly drained underlying horizon at straight slopes will evidently result in high organic carbon contents. These conditions may lead to slow decomposition of organic matter due to poorly aerated conditions caused by high moisture content that hinders microbial action (Havlin *et al.*, 1999). The clay particles also played an important role in shielding organic matter from fast decomposition (Anderson *et al.*, 1981). The highest number of vertic A horizons were formed in soils with 1% (n = 44) and 2% (n = 27) slopes.

5.3.2.2.4 Melanic soils

Melanic A horizons on steep slopes of 49% had the highest organic carbon content of 5.79% C (Figure 5.26). The lowest organic carbon (1.50% C) was found at slopes of 2%. The number of occurrences of melanic topsoils seemed to decrease as the slope percentage increased. The highest number of melanic A horizons were concentrated at slopes of 1% (n = 23) to 2% (n = 24) whilst only one horizon noted at 60% slope and only two horizons at 49% and 50% slopes. According to the results the organic carbon content was directly proportional to slope percentage in the melanic A topsoils of South Africa.

5.3.2.2.5 Orthic soils

The orthic A horizons were found at slopes ranging from 0% to 99% (Figure 5.26). This horizon is the most common topsoil (Table 5.2) and formed under diverse soil forming conditions (Soil Classification Working Group, 1991). Based on the land type data, orthic A horizons are widely distributed at almost all slope percentages. The highest organic carbon content of 4.71% C in the orthic A horizons was recorded at slopes of 70% and the lowest of 0.39% C at 0.1% slopes. There was no particular relationship between organic carbon content and slope percentage for the orthic A horizons. This may be because all topsoils that do not qualify as organic O, humic A, vertic A, and melanic A are classified as orthic A. Their properties including organic carbon content therefore vary. The 1%, 2%, and 3% slopes had the highest number of orthic A horizons namely 556, 543, and 425 respectively. This shows that the 1% to 3% slopes offer the best conditions for the formation of the orthic A horizons.

5.3.2.2.6 Silicic soils

The dorbank B horizon was found only on 5% and 30% slopes (Figure 5.27). Even though the dorbank B horizon had the lowest organic carbon content when compared to the other diagnostic horizons, the highest organic carbon (0.20% C) in this horizon was recorded at 30% slopes and the lowest organic carbon (0.10% C) at 5% slopes. The presence of a dorbank B horizon is normally a sign of very shallow soils (Soil Classification Working Group, 1991), but unfortunately only two of these horizons were noted during the land type survey.

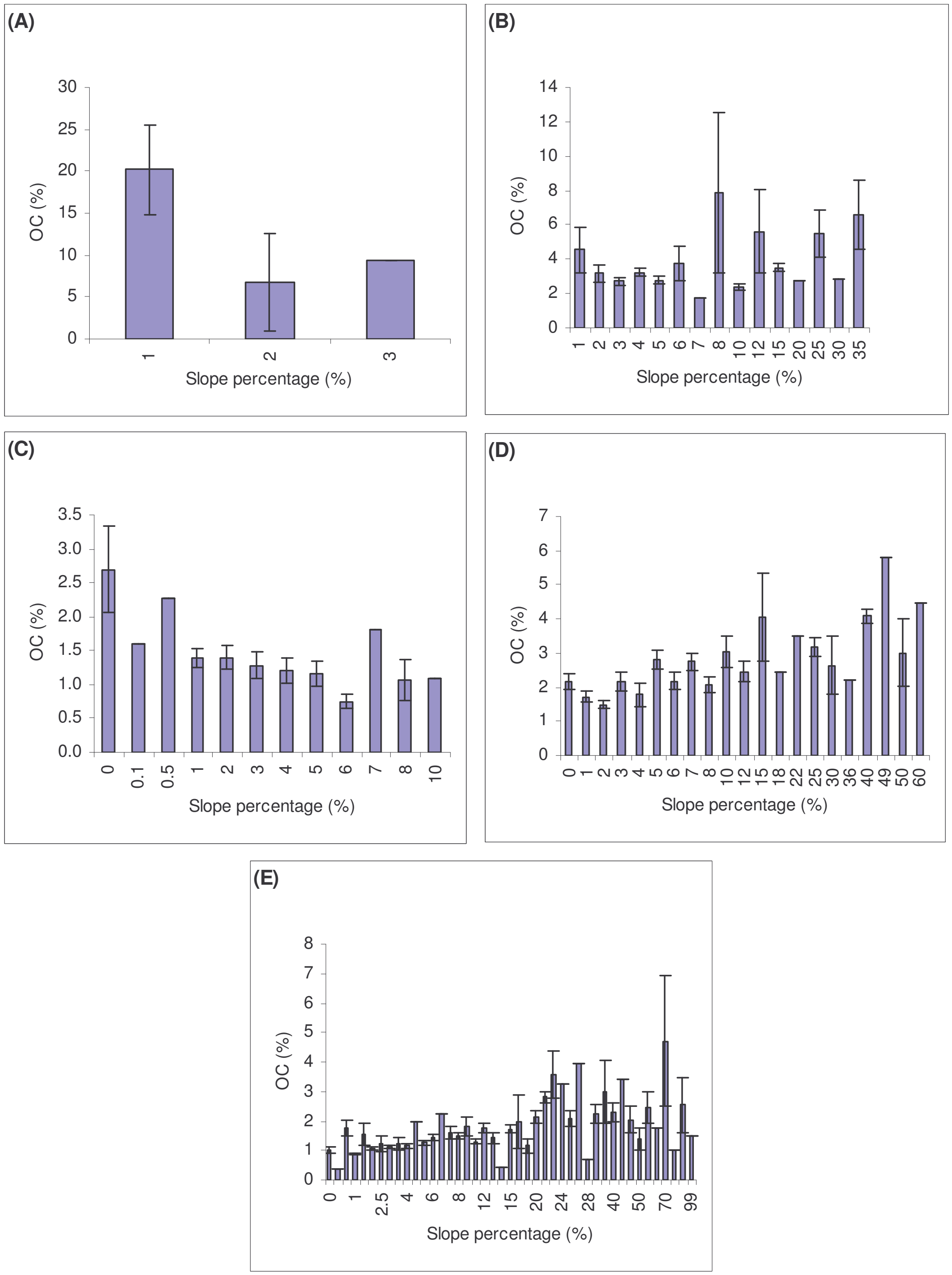


Figure 5.26 Effect of slope percentage on the organic carbon content of the diagnostic topsoil horizons: organic O (A), humic A (B), vertic A (C), melanic A (D), and orthic A (E)

5.3.2.2.7 Calcic soils

The soft carbonate B horizon was noted at slopes of less than 3% (Figure 5.27). In these horizons the highest organic carbon content (0.66% C) was found at the 1% slope and the lowest organic carbon content (0.10% C) at the 3% slope. The presence of soft carbonate at 1% and 3% slopes is evidence of effective rainfall whereby the carbonates were moved from the soils in the upper parts of the landscape and deposited into the lower areas of the landscape during soil erosion. Fey (2009) stated that calcium can also be added to the soil by water movement.

5.3.2.2.8 Duplex soils

The formation of the duplex soils was different along the landscape (Figure 5.27). Pedocutanic B horizons were found at a slope range of 0 to 70% while prismacutanic B horizons were found at a slope range of 0 to 35%. The pedocutanic B horizons noted at the 30% slopes had the lowest organic carbon content of 0.39% C while those at the 49% slopes had the highest organic carbon content of 1.19% C. The prismacutanic B horizons at the 12% slopes had the lowest organic carbon content of 0.36% while those at the 20% slopes had the highest organic carbon content of 1.29%.

The highest number of pedocutanic B horizons was noted at 2% (n = 91), 3% (n = 87), and 1% (n = 84) slopes. Most of the prismacutanic B horizons were found at 2% slopes. These horizons are characterised with a high clay content due to illuviation (Soil Classification Working Group, 1991). The possibility of the clay being deposited at the more level areas of the landscape <3% slope is very high as it may result by vertical eluviation from the overlying (A or E) horizons, or it may be lateral from the soils found at the upper slopes (Fey, 2009). This justifies the high number of duplex soils found at lower slopes.

5.3.2.3.9 Podzolic soils

The podzolic soils were found at a slope range of 1% to 50% (Figure 5.27). In these soils the highest organic carbon content of 2.78% was found at 2% slopes and the lowest organic carbon content of 0.08% at 1% slopes. Even though the organic carbon content was high at the 2% slopes there was no significant difference when compared with the amount on the other slopes. The standard error bars show a lot of variation in the data for the podzols at the 2% slopes.

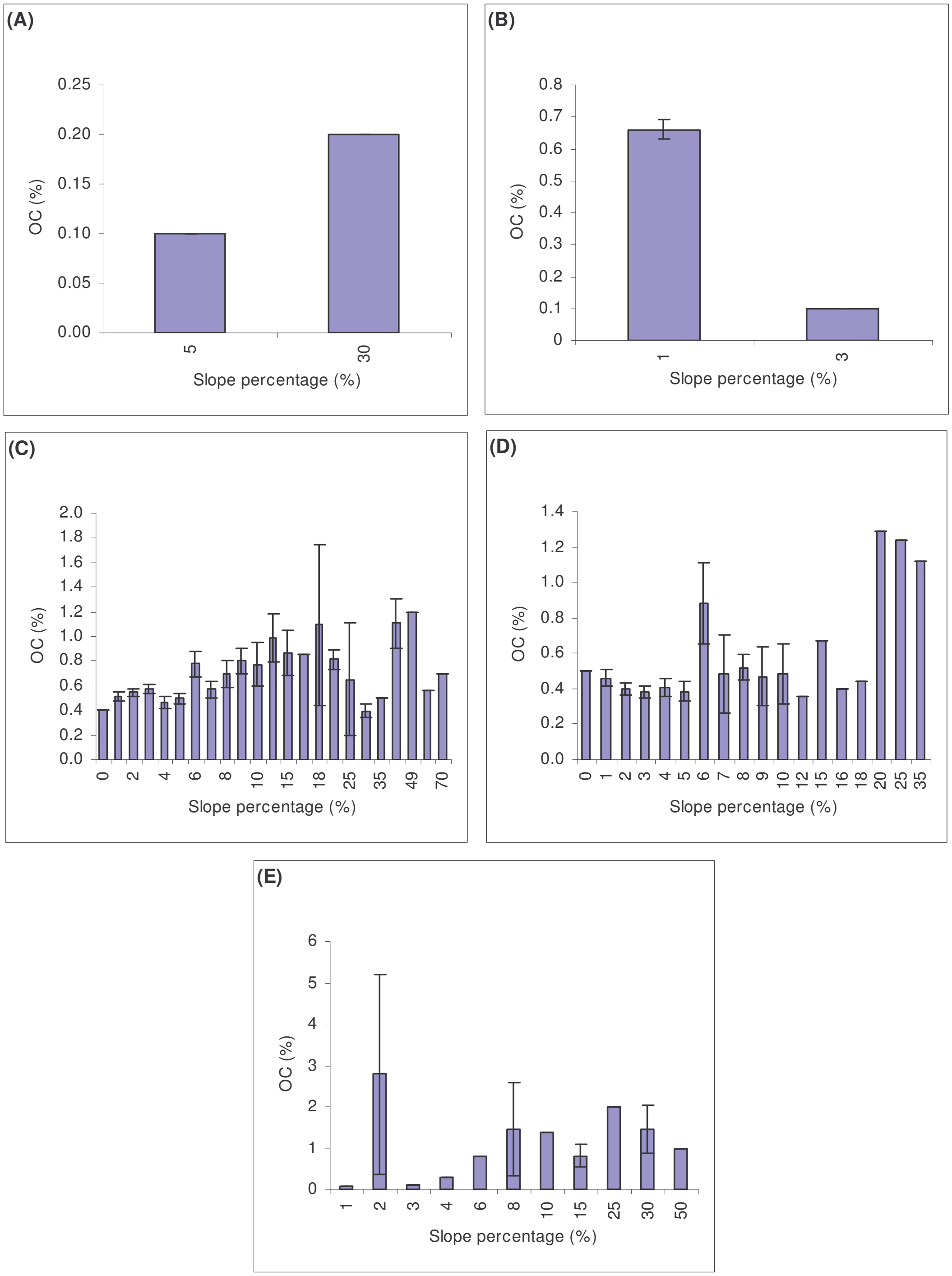


Figure 5.27 Effect of slope percentage on the organic carbon content in silicic: dorbank B (A), calcic: soft carbonate (B), duplex: pedocutanic B (C), prismacutanic B (D), and podzolic: podzol B (E) soils.

5.3.2.2.10 Plinthic soils

As displayed in Figure 5.28 the slope range in which soft plinthic B horizons (0 - 20%) were found was twice that of hard plinthic B horizons (1 - 10%). In the soft plinthic B horizons organic carbon content (0.41%) was found at the 9% slopes and the lowest organic carbon content (0.19%) at the highest 15% slopes.

The lowest (0.11%) and highest (0.54%) organic carbon contents in the hard plinthic B horizons were at slopes of 3% and 1% respectively. In the hard plinthic B horizons the organic carbon content seemed to decrease with an increase in slope percentage except at the 3% slopes where it decreased rapidly. This decrease might have been caused by changes in the type of vegetation or soil management practices which affect the amount of organic matter in the soil (Carter, 1996). The highest number of the soft plinthic B horizons was noted at the 2% slopes (n = 57) while the hard plinthic B horizons were evenly distributed in the landscape up to the 10% slopes with the 1% and 4% slopes having only one observation each.

5.3.2.2.11 Oxidic soils

The red apedal B horizons were found at a slope range of 0 to 50% and the slope range for the yellow-brown apedal B horizons was from 0 to 70% (Figure 5.28). The highest (1.41% C) organic carbon content in the red apedal B horizons was noted at the 27% slope and the lowest (0.33% C) at the 1% slope. The highest (2.53% C) organic carbon content in the yellow-brown apedal B horizons was found at the 35% slope and the lowest (0.24% C) at the 18% slope. According to the Soil Classification Working Group (1991) the yellow-brown apedal B has a higher soil water regime than the red apedal B and perhaps that is why the yellow-brown apedal B recorded a higher organic carbon content. Organic carbon accumulates more in wetter soils than in drier soils because of less decomposition. Jobbagy and Jackson (2000) reported that the amount of soil organic carbon increased as the amount of precipitation increased. Therefore if the amount of water in the soil is high, soil organic carbon content increases. The yellow-brown apedal B and the red apedal B were formed mostly at the 1% slopes.

The red structured B horizon was found in the same slopes as the yellow-brown apedal B, namely 0 - 70% (Figure 5.28). In the red structured B horizons, highest organic content was recorded at the 9% slope (2.87% C) and the lowest at the 3% slope (0.56% C). The highest numbers of red structured B horizons were noted at the 1% and 2% slopes which had 22 and

27 horizons respectively. It can be concluded that the oxidic soils are mostly formed at slopes of 1 to 2%.

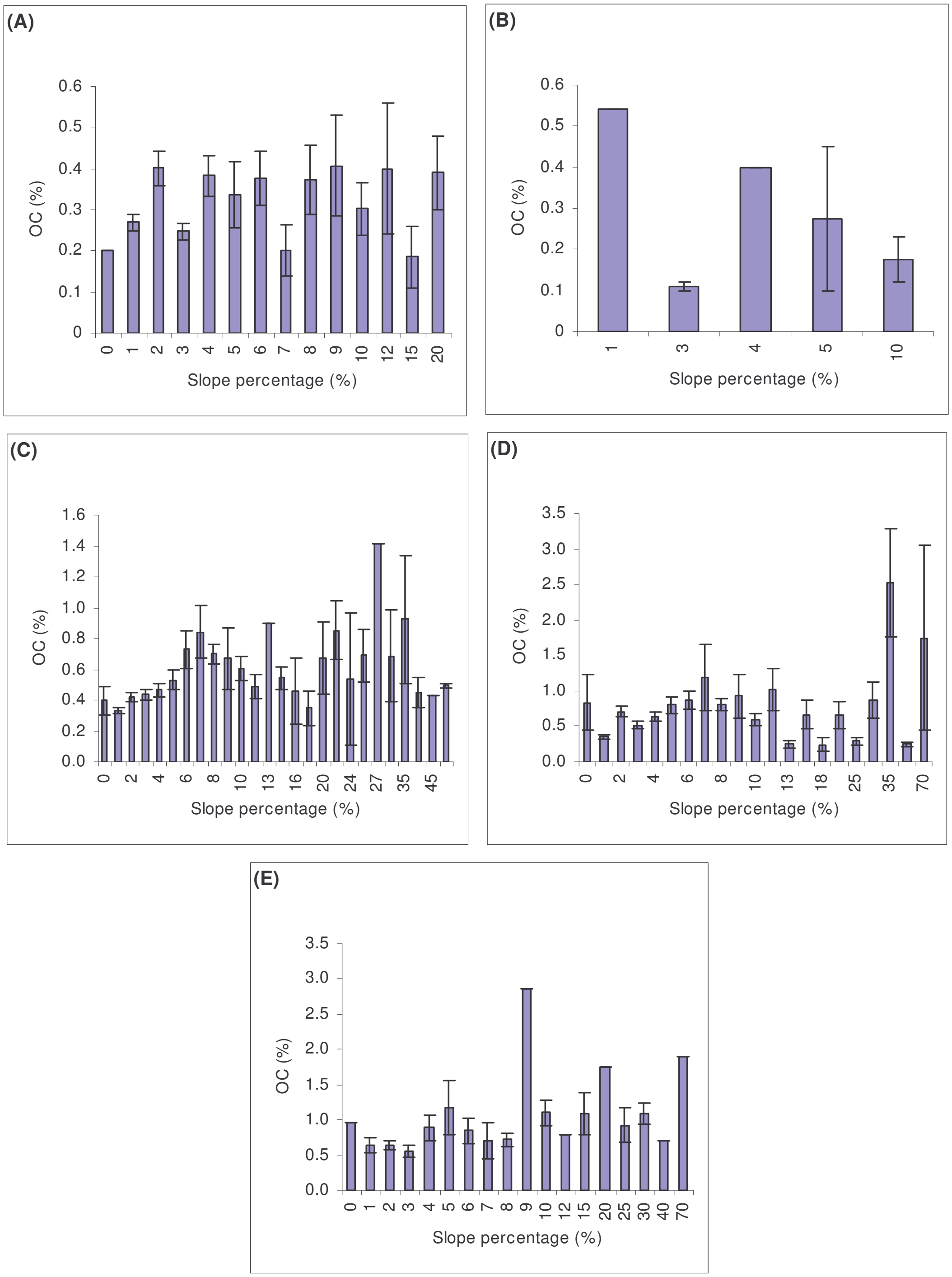


Figure 5.28 Effect of slope percentage on soil organic carbon content in plinthic soils: soft plinthic B (A), hard plinthic B (B), and oxidic soils: red apedal B (C), yellow-brown apedal B (D), and red structured B (E)

5.3.2.2.12 Gley soils

The G horizon was found at slopes between 1% and 9% and also at 20% (Figure 5.29). In this horizon the highest organic carbon content (0.59%) was found at 3% slope and the lowest organic carbon content at 9% slope. The G horizons are associated with a wet soil water regime (Soil Classification Working Group, 1991; Fey, 2009). Soils at low slopes can hold more moisture than soils on high slopes and if the underlying material has low permeability those conditions can affect the accumulation of organic carbon positively by interfering with microbial activity. Poor drainage of soils at lower slopes may also help in slowing down organic material decomposition (White, 2006). This is probably why the G horizons at the 3% slopes had high organic carbon content. Unfortunately, there was also a lot of variation in data at the 3% slopes. The highest numbers of G horizons were noted at the 2% slopes.

The gleycutanic B horizon seemed to behave in a similar manner as the G horizon in that it was also found on slopes of up to 20% (Figure 5.29). Laker (2003) points out that the gleycutanic B horizon was incorporated into the G horizon during the establishment of the Taxonomic Soil Classification System for South Africa. It is obvious that they seem to behave in the same manner as they were both not found on slopes of >20%. The highest organic carbon content in this horizon was recorded at the 6% slopes (1.36% C) but the standard error bars reveal a lot of variation. The lowest organic carbon content was found at the 7% slopes (0.16% C). No pattern can be observed for the relationship between organic carbon content and slope percentage for the gleycutanic B horizon. Most of these horizons were formed at the 2% slopes (n = 16). The 2% slopes provided the best conditions for the formation of the G and gleycutanic B horizons.

The unconsolidated material with signs of wetness was reported only at 2%, 3%, and 5% slopes (Figure 5.29). The highest organic carbon content (0.32%) was found at the 2% slopes and the lowest organic carbon (0.14%) at the 3% slopes. The difference in organic carbon between the 2% and 3% slopes was not significant. Some unspecified material with signs of wetness was found at a slope range of between 0 and 12%. Its distribution was wider than the unconsolidated material with signs of wetness. The highest organic carbon content (2.80%) in the unspecified material with signs of wetness was found at 1% slope and the lowest organic carbon content (0.13%) at 8% and 10% slopes. Based on number of observations conditions favoured the formation of unspecified material with signs of wetness at the 1% (n = 10) and 2% (n = 13) slopes.

5.3.2.2.13 Eluvial soils

Eluvial soils were found at slopes ranging from 0 to 80% (Figure 5.29). The E horizons with the highest organic carbon content of 1.44% C were at 30% slopes and those with the lowest organic carbon content of 0.20% C at 14% slopes. Generally, with a few exceptions organic carbon levels increased with higher slope percentages. Since the processes such as leaching of humus are characteristic of the formation of the E horizons (Fey, 2009), the organic carbon in the higher slope percentages was probably preserved because of availability of a less permeable underlying material and lower temperatures at higher slopes that decrease microbial activity thus aiding in organic carbon accumulation. The highest numbers of E horizons were found at the 2% slopes (n = 53). However, the occurrences of the E horizons decreased as the slope percentage increased.

5.3.2.2.14 Inceptic soils

The inceptic soils were found in different positions in the landscape. For example, the neocutanic B was found at a slope percentage range of between 0 to 99%, regic sand from 0 to 12% and stratified alluvium from 1 to 3% (Figure 5.30). Thus the neocutanic B was the most widely distributed horizon among the inceptic soils of the cumulic subgroup. The highest organic carbon content of 1.30% in the neocutanic B was at the 12% slopes and the lowest organic carbon content of 0.20% at the 20% slopes. In the regic sand the highest organic carbon content of 0.40% was noted at the 8% slopes and the lowest organic carbon content of 0.10% at the 2% slopes. The stratified alluvium had the highest organic carbon content of 0.85% at the 2% slopes and the lowest organic carbon content at the 1% slopes. These soils are mainly made up of alluvial, colluvial, or aeolian sand materials and occur mostly in midslopes to footslopes (Fey, 2009). Moges and Holden (2008) reported that as a result of erosion by water on the mid and upper slopes, sand particles were deposited at the lower slopes. This is probably why these horizons were mostly observed at lower slopes with the neocutanic B and stratified alluvium at slopes of 1% and the regic sand at slopes of 2%.

The lithocutanic B horizons were found at slopes ranging from 0 to 90% (Figure 5.31). In these horizons the highest organic carbon content of 2.15% was noted on slopes of 90% and the lowest organic carbon content of 0.31% on slopes of 0%. However, organic carbon content did not show a particular pattern in relation to slope percentage for this horizon. Most of the lithocutanic B horizons were observed at 8% slopes (n = 24). The number of occurrences of the lithocutanic B decreased as slope percentage increased starting basically at around 15%. This horizon is formed mainly from rock weathering (Soil Classification

Working Group, 1991) which was probably more dominant at the steeper slopes. Hard rock was restricted to the 1 to 4% and 15% slopes (Figure 5.31). The highest organic carbon content (0.70%) was found at the 15% slopes and the lowest organic carbon content at the 3% slopes.

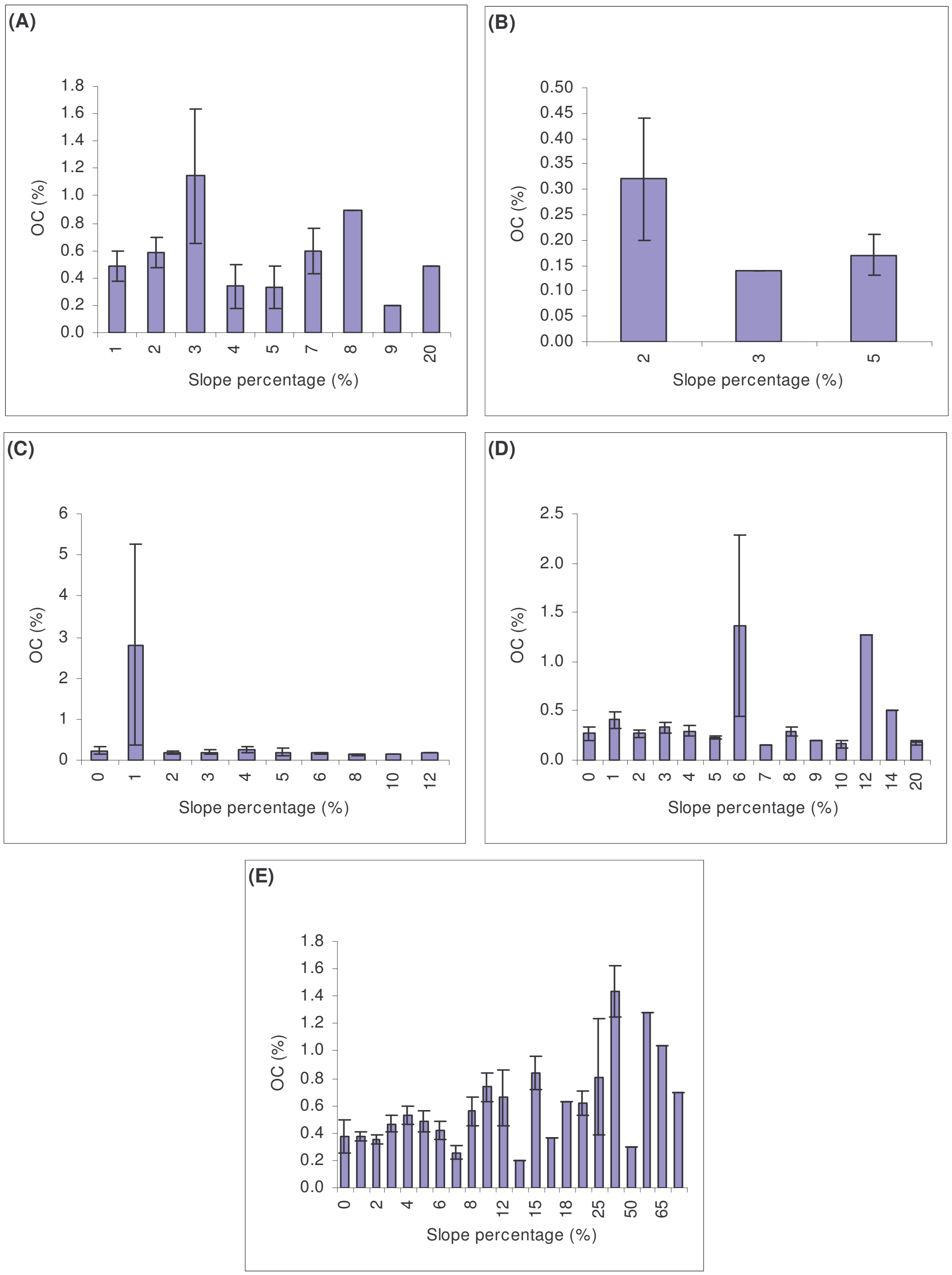


Figure 5.29 Effect of slope percentage on soil organic carbon in the gley soils: G horizon (A), unconsolidated material with signs of wetness (B), unspecified material with signs of wetness (C), gleycutanic B (D), and eluvial soils: E horizon (E)

Hard rock is a sign of shallow soils (Soil Classification Working Group, 1991). Most of the rocks were found at the 1% slopes (n = 10). The hard rock was probably exposed by erosion of the upper layers. FitzPatrick (1983) stated that the vulnerability of soil to erosion increases as the slope gradient increases and shallow soils can therefore be expected on steep slopes. Surprisingly most hard rocks were observed at level areas.

The unconsolidated material without signs of wetness was found at slopes of 1 to 30% while the unspecified dry material was found at slopes of 0 to 99% (Figure 5.31). Thus unspecified dry materials were more widely distributed than unconsolidated materials without signs of wetness. The highest organic carbon content was reported at 6% slopes for the unconsolidated material without signs of wetness (1.17% C) and at 15% slopes for the unspecified dry materials (0.57% C). Unfortunately, the standard error bars revealed a lot of variation in data in both horizons for those slope percentages. The lowest organic carbon content in the unconsolidated materials with signs of wetness and unspecified dry materials were reported at 5% (0.17% C) and 9% (0.08% C) slopes, respectively. Unspecified dry material occur mostly on 1% slopes (n = 63) and unconsolidated material with signs of wetness on 2% slopes (n = 25).

Saprolite was restricted to the 0 to 25% slope range (Figure 5.31). The highest organic carbon content of 0.59% was found at the 6% slopes and the lowest organic carbon content of 0.19% was found at the 10% slopes. According to the Soil Classification Working Group (1991) saprolite occurs in upland slopes, but the land type survey data revealed that most of the diagnostic saprolite occurs at 5% slopes (n = 12) which are lower lying slopes.

Slope percentage had an effect on the organic carbon content in some diagnostic horizons and material by influencing their soil water regime. The amount of water that can be held by the soil affects the accumulation of organic carbon by controlling the activities of the soil microbes responsible for organic carbon material decomposition. When soil water content is high decomposition is slower and organic carbon accumulates and when soil water content is low mineralisation is high leading to low levels of organic carbon (Havlin *et al*., 1999).

The horizons such as the organic O, humic A, vertic A, soft carbonate B, podzol B, soft plinthic B, hard plinthic B, red structured B, G horizon, unconsolidated material with signs of wetness, unspecified material with signs of wetness, gleycutanic B, neocutanic B, stratified alluvium, regic sand, hard rock, unconsolidated material without signs of wetness, and saprolite recorded high organic carbon contents at lower slopes. This shows that lower slopes depending on the type of soil can affect organic carbon levels positively. These results correlated with the studies of Ritchie *et al.* (2007) who reported that the organic carbon content of soils found on steep slopes where erosion is high was lower than at lower slopes which are dominated by deposition. They concluded that the amount of organic carbon in soil decreases with increasing slope angle. On the contrary, the highest organic carbon content in the melanic A, orthic A, dorbank B, pedocutanic B, prismacutanic B, red apedal B, yellow-brown apedal B, E, and lithocutanic B horizons was found on upland slopes.

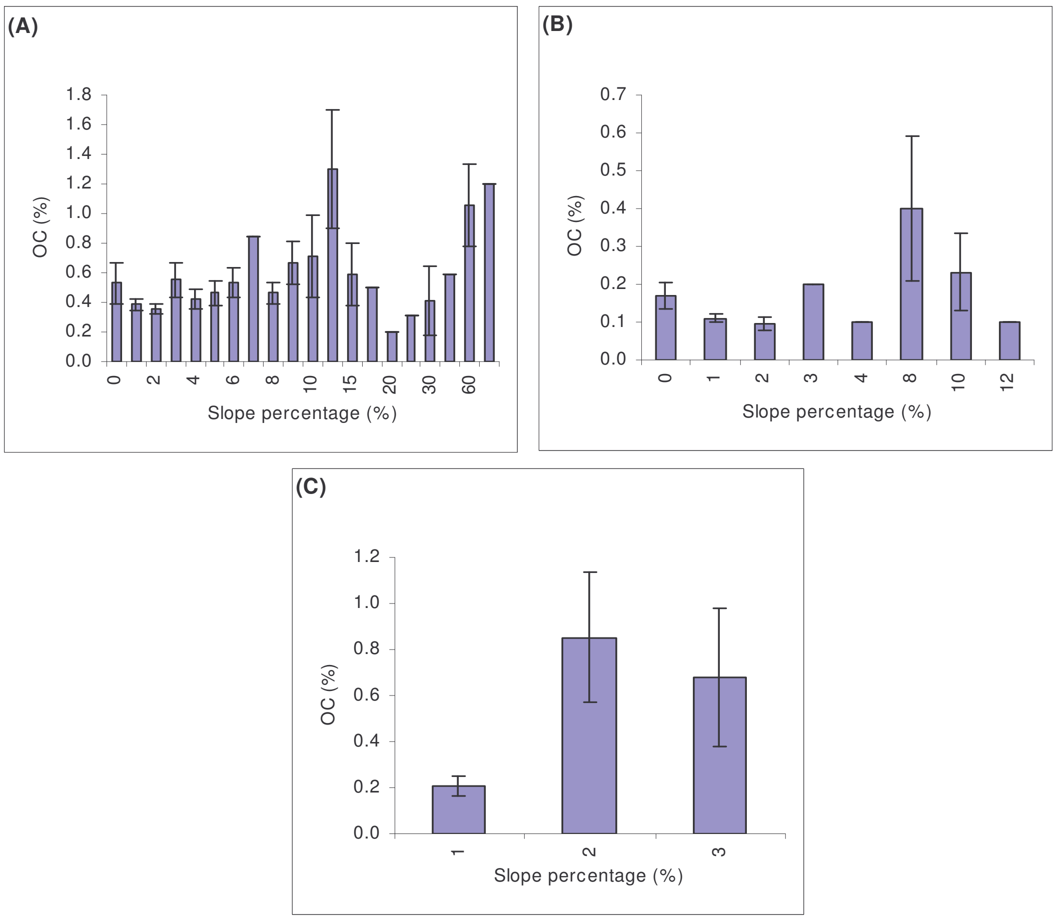


Figure 5.30 Effect of slope percentage on soil organic carbon in the cumulic subgroup of the inceptic soils: neocutanic B (A), regic sand (B), and stratified alluvium (C)

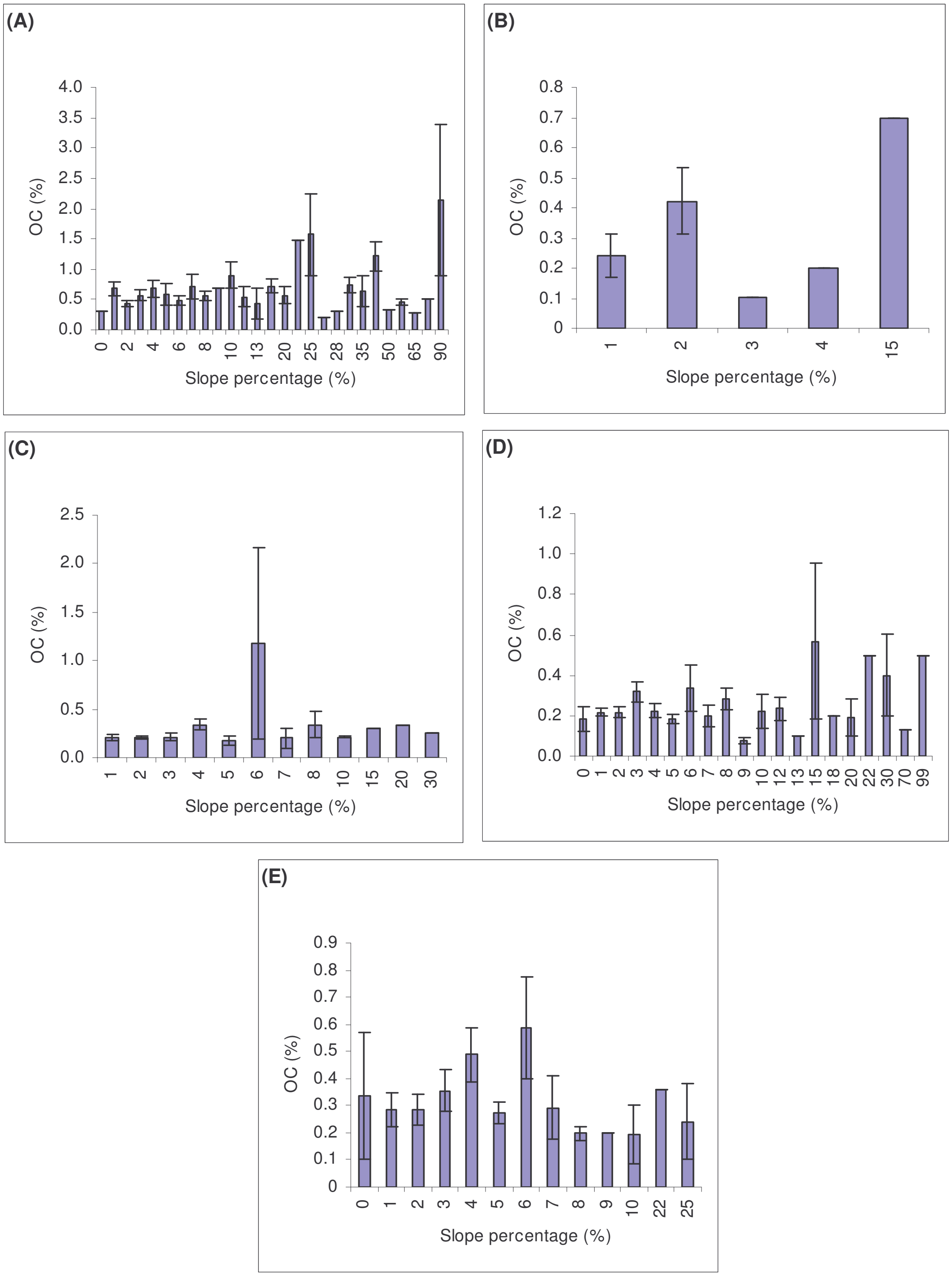


Figure 5.31 Effect of slope percentage on soil organic carbon in the lithic subgroup of the inceptic soils: lithocutanic B (A), hard rock (B), unconsolidated material without signs of wetness (C), unspecified dry material (D), and saprolite (E)

Some horizons were restricted to certain slopes which proves that slope percentage also affects soil formation. For example, the organic O horizon was found at slopes <3%, humic A

<35%, and vertic A <10%, soft carbonate <3%, prismacutanic B <35%, soft plinthic B <20%, hard plinthic B <10%, red apedal B <45%, G <7%, gleycutanic B < 20% unspecified material with signs of wetness <5%, unconsolidated material with signs of wetness <5%, regic sand <12%, stratified alluvium <3%, hard rock <15%, unconsolidated material without signs of wetness <30%, and saprolite <25%. Some of the diagnostic horizons were widely distributed throughout the landscape, namely slopes ranging from 0% to 99%. These horizons include the orthic A, neocutanic B, lithocutanic B, and unspecified dry material.

5.3.2.3 Slope type

Slope type is articulated in terms of its shape. Each type of slope determines the way in which land should be used and managed (Le Roux *et al.,* 1999). Such landscape features have been known to directly and indirectly affect the chemical properties of the soil (Razaei & Gilkes, 2005). During the transportation of soil on slopes, the shape of the slope becomes very significant in controlling on which type of slope the soil materials will settle (White, 2006). Slopes can either be level, concave, convex, or irregular. The Collins Dictionary & Thesaurus (2004) explains a concave surface as a hollow or depressed shape and a convex surface as bulging outwards. This means that soils on concave slopes can hold water better than convex slopes. The effects of three slope types, namely: convex, concave, and straight on organic carbon content in diagnostic horizons are presented and discussed in this section.

5.3.2.3.1 Organic soils

The highest organic carbon content in the organic O horizon was found at the concave slopes with an average of 23.64% and the lowest organic carbon content on straight slopes with an average of 12.50% (Figure 5.32). The organic carbon content on concave slopes was significantly higher than on convex and straight slopes. An organic O horizon is normally formed when there is accumulation of organic material as a result of slow decomposition and this happens when soil is saturated with water for a long time (Soil Classification Working Group, 1991). This results in soils having high soil organic carbon content. The concave slopes are able to offer these favourable conditions for organic carbon accumulation since they are characterised with slight to very moderate slopes. Results of this study correlate with the results of Zhang *et al.* (2006) who reported less organic carbon loss on concave slopes than on convex slopes. The diagnostic organic O horizon was found at all slope types unlike the master O horizon which was only found on concave and convex slopes. However, in both horizons the highest soil organic carbon content was found on the concave slopes.

5.3.2.3.2 Humic soils

Soils with humic A horizons had the highest organic carbon content on concave slopes (4.34%) and the lowest on straight slopes (2.93%) as displayed in Figure 5.32. The formation of a humic A horizon requires accumulation of organic matter under freely drained and aerobic conditions (Soil Classification Working Group, 1991).

The organic carbon content of the humic A horizons found on concave slopes was significantly higher than those on straight slopes, but was not significantly different from those on convex slopes. Convex slopes seemed to offer the most appropriate conditions for the formation of humic A horizons since most of them were observed on these slopes (n = 42) when compared with the occurrences of these horizons on straight (n = 14) and concave slopes (n = 14). Convex slopes probably have soils with good drainage and aerobic conditions needed for the formation of the humic A topsoils.

5.3.2.3.3 Vertic soils

As shown in Figure 5.32 the highest organic carbon content in vertic soils was recorded at convex slopes (1.23%) and the lowest on straight slopes (0.97%). This may have been brought about by more vegetation cover on the convex slopes than on the concave slopes. The type and amount of vegetation helps the soil to accumulate more organic matter (Carter, 1996). Vertic A horizons are known for their high clay content. Le Roux *et al.* (1999) and Fey (2009) stated that vertic A horizons can also be formed under cumulative conditions which are normally found at the valley bottom or level slopes. This was proven by the high number of vertic soils found on straight slopes (n = 45) when compared to those found on convex (n = 22) and concave (n = 15) slopes. There was no significant difference in organic carbon content between the vertic A horizons found on the three curve types.

5.3.2.3.4 Melanic soils

The highest organic carbon content (2.45%) in the melanic A horizons was recorded on concave slopes (Figure 5.32). The lowest organic carbon content (1.84%) was found on straight slopes. The organic carbon content in melanic soils that occur on straight slopes was significantly lower than those on concave and convex slopes. There was no significant difference in organic carbon in melanic soils found on concave and convex slopes. Most of the melanic A horizons were noted on straight slopes and the least numbers were found on concave slopes. Le Roux *et al.* (1999) stated that melanic A horizons are usually found on young landscapes. Most of the melanic A horizons were formed on straight slopes (n = 51).

5.3.2.3.5 Orthic soils

The highest organic carbon content (1.58%) was reported in orthic A horizons on convex slopes (Figure 5.32). Orthic A horizons on straight slopes had the lowest organic carbon content, namely 1.07%. The orthic A horizons are found within a broad range of soil forming conditions (Soil Classification Working Group, 1991). The orthic A horizons on straight slopes had significantly lower organic carbon content than those found on convex slopes.

However, when studying the number of occurrences there seemed to be much more orthic A horizons on straight slopes (n = 669) than on convex (n = 608) and concave (n = 366) slopes. Even though there is no particular pattern in which these horizons are formed, their quality differs according to their chemical and physical properties as well as their water content (Soil Classification Working Group, 1991). This means that some orthic A horizons will therefore be formed on gentle slopes, in alluvial or/and anaerobic conditions on concave or convex soils which produce soils with different drainage conditions. The organic carbon content of these soils will therefore differ vastly depending on the soil forming conditions.

5.3.2.3.6 Silicic soils

The dorbank B horizon was only observed on straight slopes (Figure 5.33). Le Roux *et al.* (1999) stated that the dorbank B horizon is usually formed on gentle slopes and this was proven by the results of the land type survey data. Unfortunately, not many observations of the dorbank B horizons were found but it is clear that this horizon has the lowest organic carbon content amongst all identified diagnostic horizons and materials in South Africa.

5.3.2.3.7 Calcic soils

The formation of a soft carbonate B horizon was also restricted to convex slopes only (Figure 5.33). This horizon is actually characteristic of soils formed under dry conditions (Fey, 2009). Very few soils with soft carbonate B horizons were found during the land type survey (n = 3). This is probably because this horizon is one of the new additions to the 1991 taxonomic system for classifying South African soils (Laker, 2003).

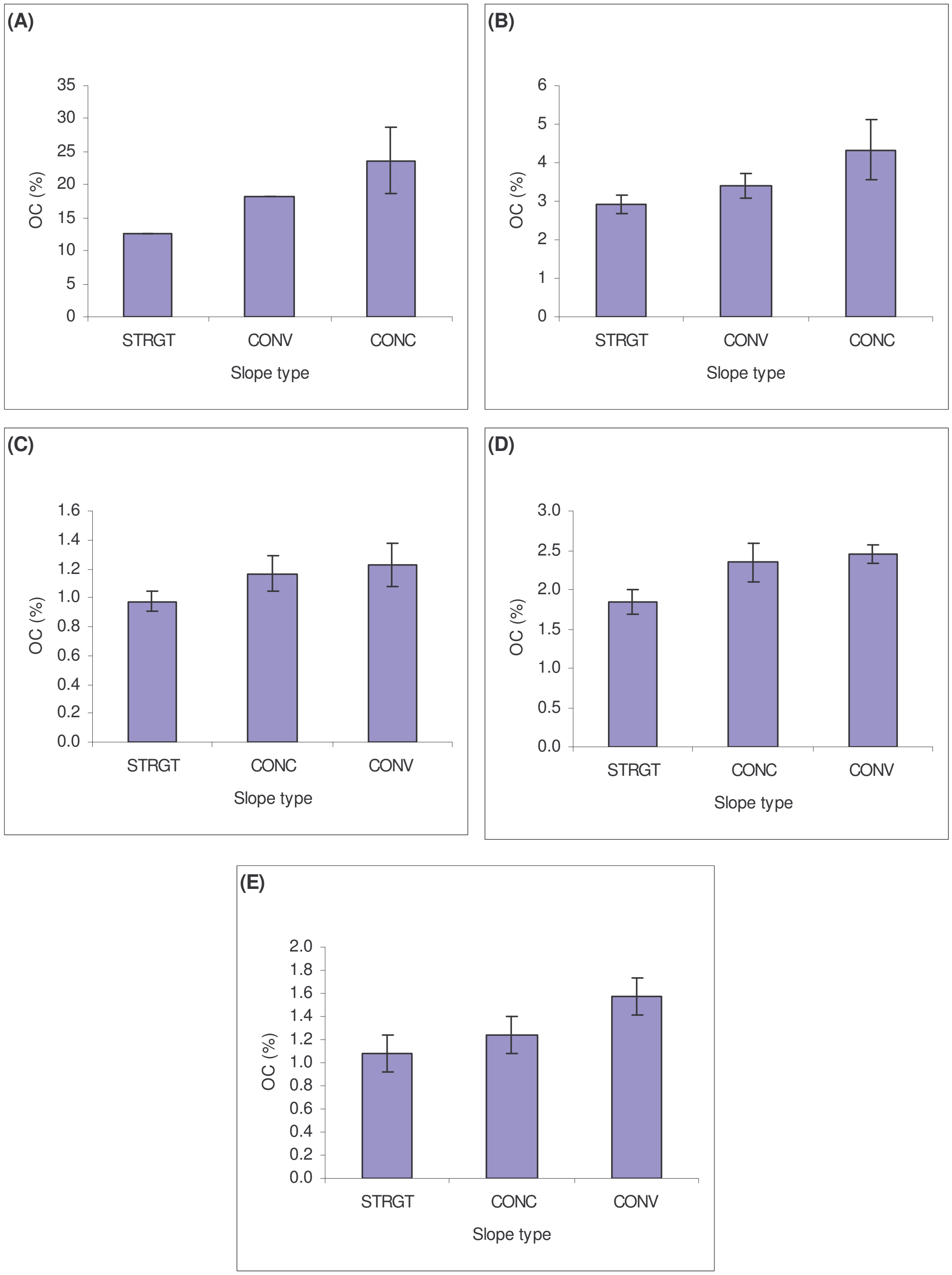


Figure 5.32 Effect of slope type on the organic carbon content of the diagnostic top soil horizons: organic O (A), humic A (B), vertic A (C), melanic A (D), and orthic A (E)

5.3.2.3.8 Duplex soils

The organic carbon content in pedocutanic and prismacutanic B horizons followed the same pattern along the landscape as shown in Figure 5.33. The highest organic carbon content was found in soils on convex slopes with 0.41% in the prismacutanic B and 0.55% in the pedocutanic B. The lowest organic carbon content was found in soils on straight slopes with 0.63% in the prismacutanic B and 0.69% in the pedocutanic B. The organic carbon content in the pedocutanic B horizons on convex slopes was significantly higher than that on straight slopes, but was not significantly different from the soils on concave slopes. There was no significant difference in organic carbon content between soils on straight slopes and concave slopes in both horizons. However, the organic carbon content in prismacutanic B horizons on convex slopes was significantly higher than on straight and concave slopes. The straight slopes seemed to provide the most suitable conditions for the formation of the pedocutanic B (n = 102) and prismacutanic B (n = 186) horizons since the highest number of observations were found there.

5.3.2.3.9 Podzolic soils

The highest organic carbon content of 2.11% in the podzol B horizons was found in soils on straight slopes (Figure 5.33). The lowest organic carbon content of 0.76% in these horizons was in soils on concave slopes. The standard error bars show a lot of variation in the data observed on straight slopes. Most of the podzol B horizons were formed on convex slopes (n = 9). The difference in organic carbon content between the podzol B horizons from three slope types was not significant.

5.3.2.3.10 Plinthic soils

As shown in Figure 5.34 the highest organic carbon content in the soft plinthic B horizons was recorded on convex slopes (0.39%) and the lowest on concave slopes (0.29%), whereas the opposite was true for the hard plinthic B horizons, with the highest on concave slopes (0.33%) and the lowest on convex slopes (0.20%). The organic carbon content of the soft plinthic B horizons on concave slopes was significantly lower than those on convex slopes while there was no significant difference in organic carbon content between the soft plinthic B horizons on straight and convex slopes. There was no significant difference in organic carbon content between the hard plinthic B horizons found on three different slopes types. The hard plinthic B horizons on straight and convex slopes had an equal number of observations (n = 3). Convex slopes had the highest number of soft plinthic B horizons (n = 72) followed by straight slopes (n = 68).

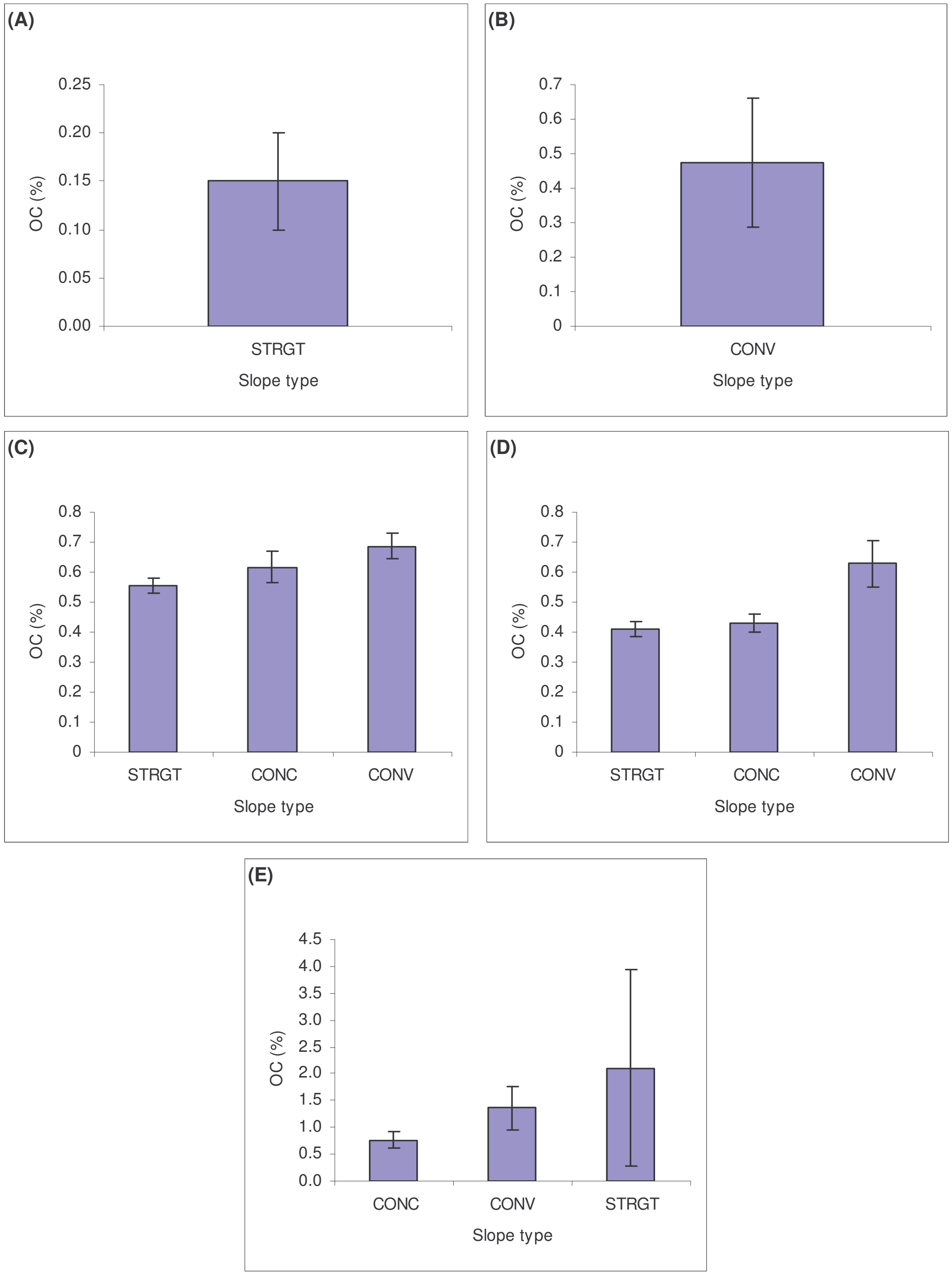


Figure 5.33 Effect of slope type on soil organic carbon content in the silicic soils: dorbank B (A), calcic soils: soft carbonate (B), duplex soils: pedocutanic B (C), prismacutanic B (D), and podzolic soils: podzol B (E)

5.3.2.3.11 Oxidic soils

The highest organic carbon content in the red apedal B horizons (0.66%) was found on convex slopes whereas it was reported on the concave slopes for the yellow-brown apedal B horizons (0.78%) and the red structured B horizons (1.06%; Figure 5.34). The lowest organic carbon in the red apedal B horizons (0.51%) was found on concave slopes and on straight slopes for the yellow-brown apedal B horizons (0.45%) and the red structured B horizons (0.64%).

However, the yellow-brown apedal B horizons were restricted to straight and concave slopes only and were not found on convex slopes. This is probably because the yellow-brown apedal B horizons need wetter conditions that result in the yellow soil colour that is characteristic of this horizon (Soil Classification Working Group, 1991). The convex soils probably lack sufficient water for the formation of a yellow-brown apedal B.

The organic carbon content in the red apedal B horizons on convex slopes was significantly higher than that found on concave and straight slopes. There was no significant difference in organic carbon content in the yellow-brown apedal B horizons that were found on both straight and concave slopes.

The organic carbon content in the red structured B horizons on straight slopes was significantly lower than that on convex and concave slopes. Most of the red apedal (n = 270) and red structured B (n = 53) horizons were observed on convex slopes. This shows that the formation of these horizons is actually attributable to good drainage sites along the landscape. The outward bulge of the convex slopes helps the soils found there to have free drainage. An equal number (n = 3) of yellow-brown apedal B horizons were reported on straight and concave slopes. However, it is clear that their formation requires a wetter soil water regime than the other oxidic soils which can be possible on straight and concave slopes.

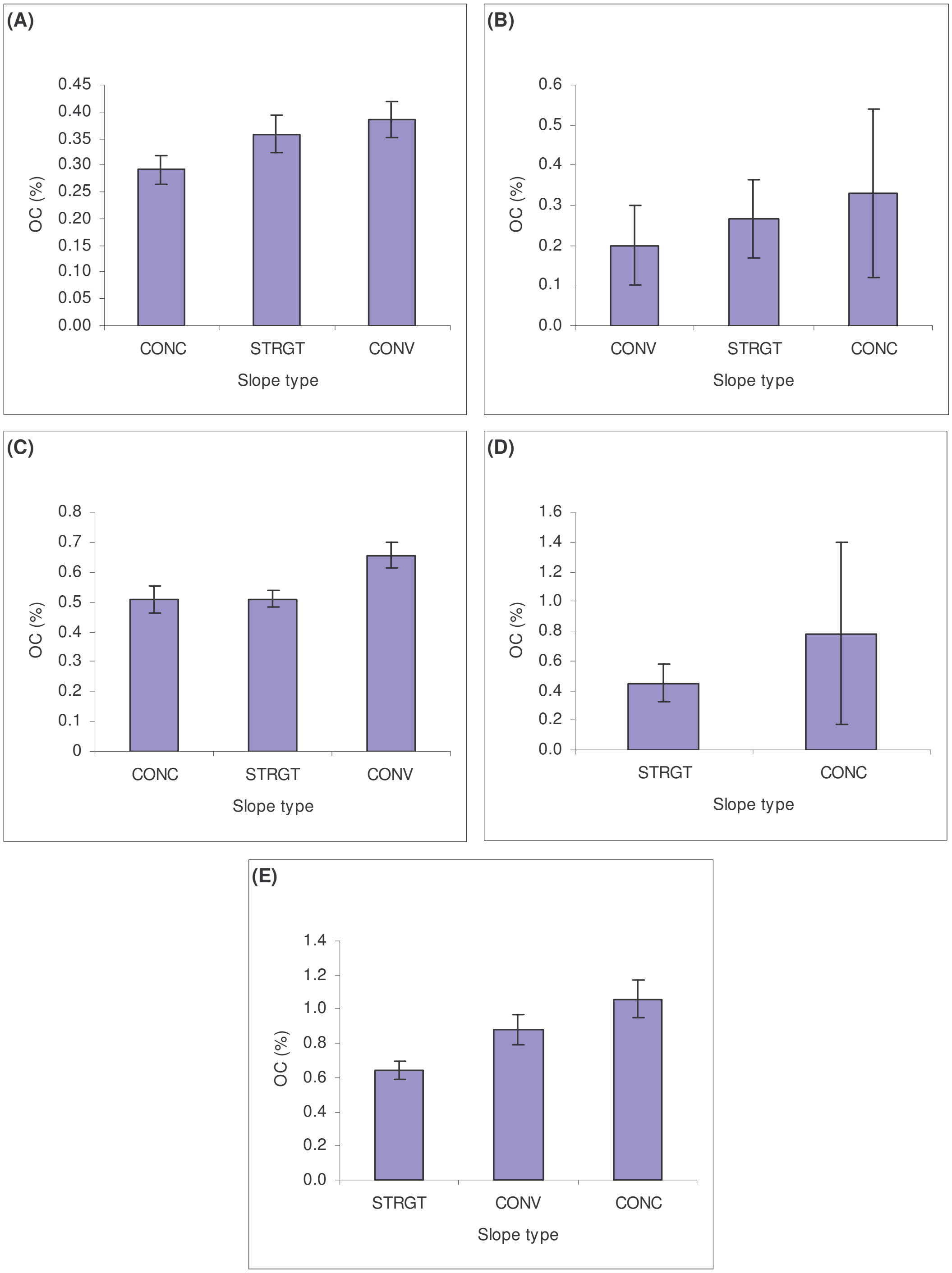


Figure 5.34 Effect of slopes type on soil organic carbon content in the plinthic soils: soft plinthic B (A), hard plinthic B (B), and oxidic soils: red apedal B (C), yellow-brown apedal B (D), and red structured B (E)

5.3.2.3.12 Gley soils

As displayed in Figure 5.35 the highest organic carbon content was observed in the G horizons (1.02%) that were found on convex slopes. However, the unconsolidated (0.33%) and unspecified (3.73%) materials with signs of wetness on concave slopes had the highest organic carbon content as did gleycutanic B horizons (0.40%) on straight slopes. The concave slopes allowed for a higher accumulation of organic carbon in the unspecified and unconsolidated materials with signs of wetness. If the water content was high the concave slopes were able to provide anaerobic conditions that hinder the activity of soil microorganisms resulting in slower decomposition rate (Havlin *et al*., 1999). However, the lowest organic carbon content in the G (0.48%) and gleycutanic B (0.28%) horizons was reported on concave slopes while it was on convex slopes for the unspecified materials with signs of wetness (0.22%) and on straight slopes for the unconsolidated materials with signs of wetness (0.13%). The unconsolidated materials with signs of wetness were not found on convex slopes. Le Roux *et al.* (1999) stated that the unconsolidated materials with signs of wetness need intermittent saturation with water or cumulative moist conditions. These conditions probably occur on convex slopes.

There was no significant difference in organic carbon content between the G horizons found on concave and straight slopes. The organic carbon content in G horizons on convex slopes was significantly higher than that on concave and straight slopes. Unconsolidated material with signs of wetness on straight and concave slopes differs significantly. However, the organic carbon content in neither the gleycutanic B horizons nor the unspecified materials with signs of wetness differed significantly between the three slope types. For all the diagnostic gley horizons, the highest number of observations was made on straight slopes. This shows that hydromorphic soils are usually formed at the valley bottoms which are straight and offer the alluvial conditions required for their formation (Le Roux *et al.,* 1999).

5.3.2.3.13 Eluvial soils

The E horizons on convex slopes proved to have the highest organic carbon content of 0.66%, whereas those on concave slopes had the lowest organic carbon content of 0.41% (Figure 5.35). The organic carbon content in the E horizons that were found on convex slopes was significantly higher than that on concave and straight slopes. There was no significant difference in organic carbon content of E horizons on concave and straight slopes. Generally, the diagnostic E horizons behaved in the same manner as the master E horizons (Section 4.3.2.3.3) since both the highest organic carbon content was reported on convex slopes and the lowest on concave slopes. There was probably more vegetation production on the convex slopes which contributed to the addition of organic material to the soil (Carter, 1996). Most of the E horizons were observed on convex slopes, namely 110. The formation of this horizon is characteristic of eluviation of materials such as clay, oxide minerals, and humus (Fey, 2009). The convex and straight slopes seemed to offer those distinctive conditions but their formation also depends on the permeability of the underlying materials.

5.3.2.3.14 Inceptic soils

There is no particular pattern in the behaviour of organic carbon content in the cumulic subgroup of inceptic soils (Figure 5.36). The highest organic carbon content was reported in the neocutanic B (0.68%) and regic sand (0.24%) horizons that were found on convex slopes. The lowest organic carbon content in the neocutanic B horizons (0.42%) was on straight slopes and on concave slopes for the regic sand (0.12%). The amount of organic carbon in the neocutanic B horizons on straight slopes was significantly lower than on concave and convex slopes. A significant difference in organic carbon content in the regic sand was found between those on concave and convex slopes, which was high in the former slopes. The highest organic carbon content in stratified alluvium horizons was reported in those on straight slopes (0.56%), whilst the lowest was on concave slopes (0.10%).

These horizons were formed from materials of either alluvial, colluvial, or aeolian sources and depend highly on the environment (Fey, 2009). The highest number of neocutanic B horizons and the stratified alluvium horizons were found on straight slopes. Most regic sand horizons were noted on convex slopes.

In the lithocutanic B horizons, the organic carbon content was highest in those on concave slopes (0.80%) and lowest in those on straight slopes (0.61%) as shown in Figure 5.37. There was no significant difference in organic carbon content between the lithocutanic B horizons found on all three slope types. The highest organic carbon content in hard rock was found on convex slopes (0.40%) and the lowest on straight slopes (0.10%). The difference between the organic carbon content in the hard rock on straight and convex slopes was not significant. These horizons are signs of very shallow soils and they were found mostly on straight and convex slopes. On these two slope types there were 10 observations for hard rock and 94 observations for lithocutanic B horizons.

As displayed in Figure 5.37 the unconsolidated materials without signs of wetness recorded the highest organic carbon content on straight slopes (0.37%) and the lowest on concave slopes (0.24%). The organic carbon content of these materials was not significantly different on the three slopes types, namely concave, convex, and straight. Most of the unconsolidated dry material was found on straight slopes (n = 35). Although the organic carbon content was not significantly different between slope types the highest carbon content was reported in the unspecified dry materials that occur on convex slopes (0.29%) and the lowest on concave slopes (0.26%; Figure 5.37). The unspecified dry materials were mostly observed on straight slopes (n = 73). Similar to the unspecified dry materials the amount of organic carbon in saprolite soils was not significantly different between the three slopes types. However the highest carbon content was reported on straight slopes (0.43%) and the lowest on concave slopes (0.31%). Most of the saprolites were found in soils that were formed on convex slopes (n = 37).

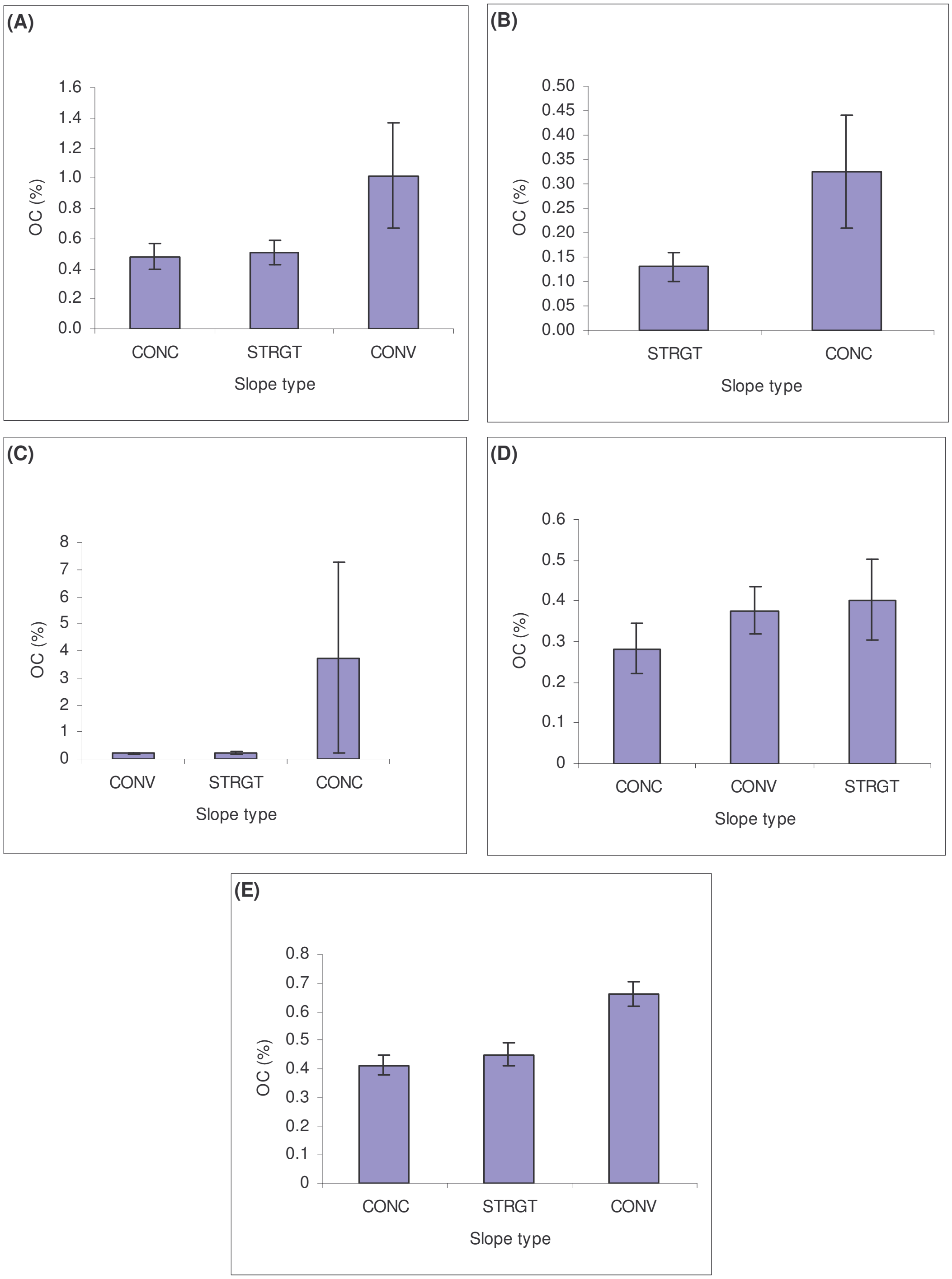


Figure 5.35 Effect of slope type on soil organic carbon in the gley soils: G horizon (A), unconsolidated material with signs of wetness (B), unspecified material with signs of wetness (C), gleycutanic B (D), and eluvial soils: E horizon (E)

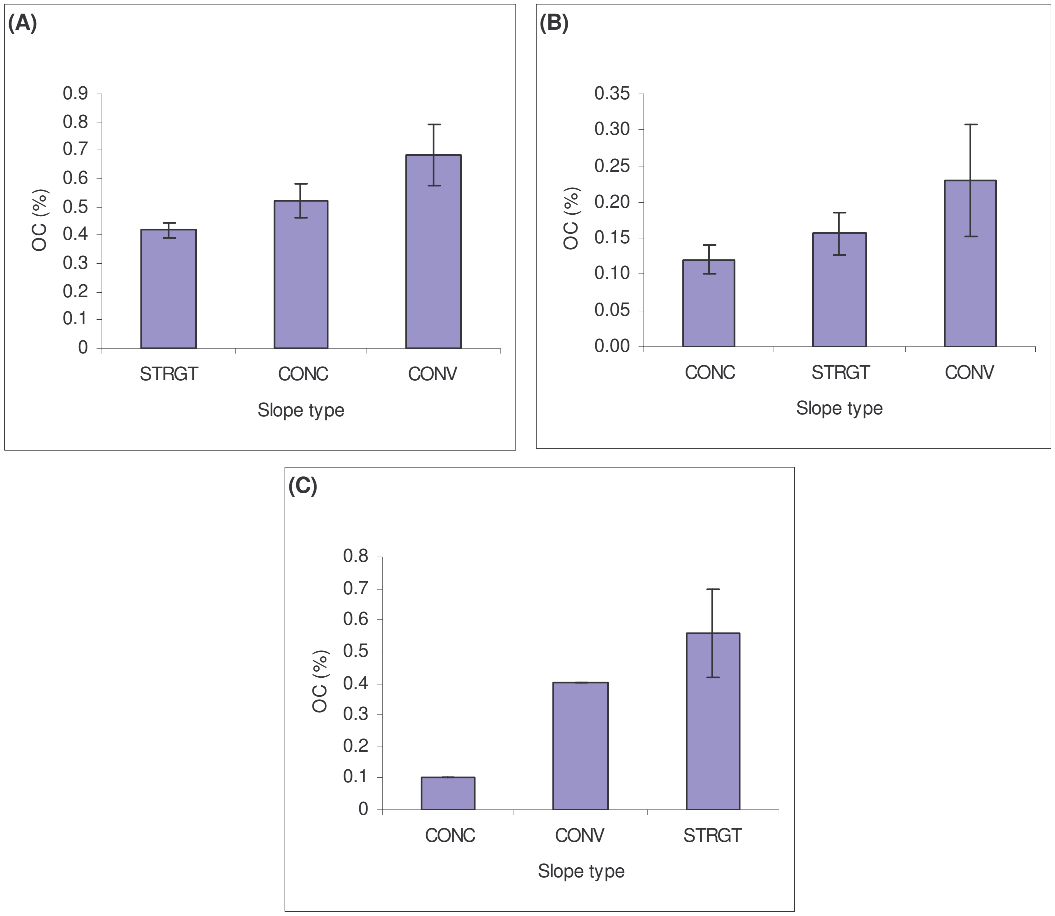


Figure 5.36 Effect of slopes type on soil organic carbon in the cumulic subgroup of the inceptic soils: neocutanic B (A), regic sand (B), and stratified alluvium (C)

Both the organic O and humic A had the highest organic carbon content when these horizons occur on concave slopes. Concave slopes are mostly found in midslopes and sometimes at the crests and have moderate slopes (Le Roux *et al.,* 1999). They can also provide the conditions needed for the accumulation of organic material under moist climates by being able to retain water for longer, depending on the permeability of the underlying horizon. This may hinder or interfere with microbial activity thus allowing for accumulation of organic carbon. The difference might lie in the anaerobic and aerobic conditions necessary for the formation of the organic O and humic A horizons respectively. For example humic A horizons require free drained conditions to develop (Fey, 2009). Ritchie *et al.* (2007) also reported higher soil organic carbon contents on concave slopes than on convex slopes.

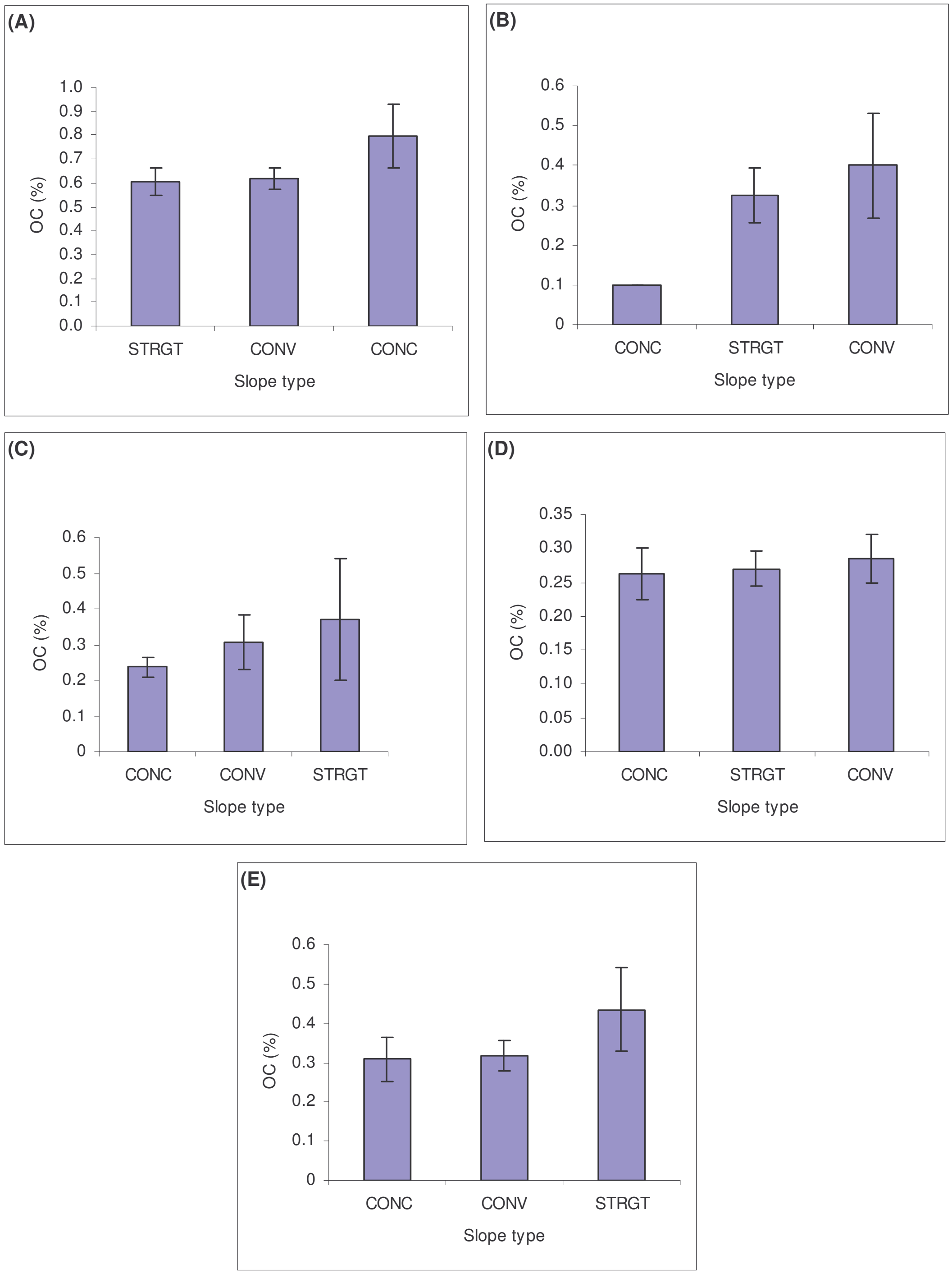


Figure 5.37 Effect of slopes type on soil organic carbon in the lithic subgroup of the inceptic soils: lithocutanic B (A), hard rock (B), unconsolidated material without signs of wetness (C), unspecified dry material (D), and saprolite (E)

The other three topsoil horizons: vertic A, melanic A, and orthic A followed the same pattern in their formation in the landscape. In these three horizons the highest organic carbon content was reported when they were found on convex slopes and the lowest when they were found on straight slopes. Convex slopes are usually found on moderate to sloping areas or knolls and the soils found here require sound management due to their sensitivity to soil erosion (Le Roux *et al*., 1999). Soil erosion increases as slope gradient increases (FitzPatrick, 1983) so sound land use practices have to be applied on convex slopes mostly. Most of the vertic A, melanic A, and orthic A horizons were formed on straight slopes with very low slope elevation.

Although the diagnostic subsoil horizons in South Africa are characterised by a very low organic carbon content (Barnard, 2000) the type of slope seemed to have an effect depending on the type of soil. The convex slopes recorded the highest organic carbon content in the following horizons: pedocutanic B, prismacutanic B, soft plinthic B, red apedal B, neocutanic B, regic sand, G, and E horizons. These slopes had the lowest organic carbon contents in the hard plinthic B horizon and the unspecified material with signs of wetness. Vegetation differences as well as land use practices may have caused the differences in organic carbon content (Carter, 1996).

The concave slopes recorded the highest organic carbon content in the following horizons: hard plinthic B, yellow-brown apedal B, red structured B, unconsolidated material with signs of wetness, unspecified material with signs of wetness, and lithocutanic B. Ritchie *et al*. (2007) also reported higher organic carbon levels on lower lying areas and depressions than on the upland slopes or on ridges. They added that this was probably because of higher deposition of soil as well as higher water content in those areas which contributed to the accumulation of soil organic carbon. The lowest organic carbon content on concave slopes was in the podzol B, soft plinthic B, red apedal B, G horizon, gleycutanic B, E horizon, regic sand, stratified alluvium, hard rock, saprolite, and unconsolidated and unspecified dry materials.

The highest organic carbon content on straight slopes was found in the podzol B, gleycutanic B, stratified alluvium, saprolite, and unconsolidated material with signs of wetness. On these slopes the lowest organic carbon content was in the prismacutanic B, yellow-brown apedal B, red structured B, unconsolidated material with signs of wetness, neocutanic B, and lithocutanic B horizons.

Some diagnostic horizons were restricted to certain types of slopes. The dorbank B was only found on straight slopes, the soft carbonate B horizon on convex slopes only, yellow-brown apedal B on straight and concave slopes and the unconsolidated material with signs of wetness on straight and concave slopes only. However, the organic carbon content of the different diagnostic horizons and materials also depends highly on the interaction of other soil forming factors such as climate, parent material, and vegetation that are associated with the particular horizon as well the type of environmental conditions found and influenced by a certain slope type.

5.3.2.4 Slope aspect

The variations in slope aspect highly influence the chemical properties of soils as well as the type of vegetation that grows on them (Buol *et al*., 1989; Le Roux *et al*., 1999). Slope aspect affects the levels of soil organic carbon by influencing the micro-climate of an area with the main factors being water and temperature (Carter, 1996). This in turn affects the types of soils formed in that area. A slope can face north, south, east, or west or towards any position that falls between the four major cardinal points. Barry (2008) explained that the environmental conditions on slopes in the southern hemisphere are different from the soils on the northern hemisphere. He stated that the south eastern slopes have a lower temperature and higher moisture content when compared to the north western slopes in the southern hemisphere and the opposite is true for the northern hemisphere. Le Roux *et al.* (1999) stated that in the southern hemisphere, the south eastern slopes are colder and wetter than the north western slopes. The difference is caused by differences in the duration for which the slopes receive sunlight. This affects the organic carbon content of soils because the processes of decomposition and mineralisation which bring about the ultimate reduction in organic matter content depend on soil temperature and water content (Kirschbaum, 1995; Jobbagy & Jackson, 2000). Therefore the effects of slope aspect on the organic carbon content in diagnostic horizons are dealt with in this section and shown in Figures 5.38 to 5.43).

5.3.2.4.1 Organic soils

Soils with organic O horizons were found on the south, east, west, and level slopes (Figure 5.38). The highest organic carbon content (28.40%) was reported on level slopes and the lowest (10.93%) on eastern slopes. Level slopes probably affected organic carbon levels positively because of higher water content which promotes accumulation of organic material by lower microbial activity. Gregorich *et al.* (1998) reported higher organic carbon levels on lower slope positions and level areas because of erosion of the materials from the upper slopes and their deposition at the level areas. Soils at level slopes are in some instances saturated for longer periods (White, 2006). This provides anaerobic conditions which promote accumulation of soil organic carbon. The organic carbon content of organic soils at level slopes was significantly higher than at the eastern slopes.

5.3.2.4.2 Humic soils

The humic topsoils were found at different slope aspects (Figure 5.38). However, the highest organic carbon content of 5.23% was reported in humic A horizons that were situated at northern slopes and the lowest organic carbon content of 2.90% at western slopes. In South Africa the north and westerly slopes are normally warm and dry (Le Roux *et al.*, 1999). It was therefore expected that the highest amount of organic carbon in these humic horizons would be found on the colder and the wetter slopes such as the south easterly slopes. The northern slopes probably had a higher organic carbon content because there was greater vegetation production due to warmer temperatures. Fisher *et al*. (1994) reported higher organic carbon storage after introducing exotic grass species in the savannas of Columbia. The type of vegetation may also have played an important role in the increasing organic carbon levels on the northern slopes (Carter, 1996). However, the difference in organic carbon content at the northern slopes, south western, level, southern, south eastern, and eastern slopes was not significant. The organic carbon content at the western, north eastern, and north western slopes was significantly lower than at the northern slopes. Most of the humic topsoils were reported at the southern slopes (n = 30). According to the Soil Classification Working Group (1991) the humic topsoils are mostly formed in cool and moist climates. In South Africa the southern slopes are cooler and wetter.

5.3.2.4.3 Vertic soils

The highest organic carbon content in the vertic topsoils was found at the north eastern slopes (2.45%) and the lowest at the level slopes (0.83%; Figure 5.38). The warmer temperatures of the northern slopes combined with the moist conditions of the eastern slopes probably helped in improving biomass production therefore increasing the levels of organic carbon in the north eastern slopes. The organic carbon content at the north eastern slopes was not significantly different from the organic carbon content at the south eastern and north western slopes but was significantly higher than the organic carbon content at the level, east, south, west, and northern slopes. The highest numbers of vertic topsoils were reported at the southern slopes (n = 20). The organic carbon content on the northern slopes was expected to be lower than on the eastern and southern slopes since slower decomposition on the latter slopes which are cooler and wetter were expected to promote the accumulation of organic carbon. Soil organic carbon content is positively related to precipitation and negatively related to temperature (Lemenih & Itanna, 2004).

5.3.2.4.4 Melanic soils

As displayed in Figure 5.38 melanic A horizons were reported at different slope aspects. The highest organic carbon content in the melanic topsoils was found at the north western slopes (2.46%) and the lowest at the level slopes (1.65%). Organic carbon at the level slopes was significantly lower than at the north eastern, western, eastern, northern, and north western slopes. The north westerly slopes are normally hotter and drier and mineralisation of organic matter was expected to be higher than at the south easterly slopes which are cooler and wetter. Surprisingly, the standard error bars revealed that the difference in organic carbon content between the south easterly and north westerly slopes was not significant. The temperature differences were expected to have an effect on soil organic carbon contents. The melanic soils are normally formed under semi-arid to sub-humid climates and sometimes under humid climates (Soil Classification Working Group, 1991). Van der Merwe *et al*. (2002) stated that the formation of melanic soils highly depends on climate with more than 75% of them being formed in semi-arid areas with a rainfall of between 550 mm and 800 mm. According to the results of this study the highest numbers of melanic topsoils were reported on eastern slopes (n = 37) which are cool and wet. A certain amount of rainfall, preferably not higher than 800 mm and not less than 550 mm, is needed for moderate leaching intensity for the formation of melanic A horizons.

5.3.2.4.5 Orthic soils

The orthic topsoils were also found within a diverse range of slope aspects (Figure 5.38). Orthic A horizons at the south western slopes had the highest organic carbon content of 1.73% while those at the level slopes had the lowest organic carbon content of 1.01%. As expected the organic carbon content in the south eastern and south western slopes was significantly higher than at the western, northern, north western, and eastern slopes. This is because of the climatic conditions found at the south slopes which are colder and wetter and favour the accumulation of soil organic carbon. Under cool temperatures biological activity decreases therefore soil organic carbon is conserved (Sims & Nielsen, 1986). The organic carbon content in the orthic A horizons at level slopes was significantly lower than at any other slopes where they were found. The low organic carbon content in the orthic A horizons on the levels slopes may have been caused by cultivation or erosion. Soil erosion removes the topsoil and therefore reduces the amount of organic carbon in the soil and redistributes it to other parts of the landscape (Gregorich *et al.,* 1998; Stevenson & Cole, 1999). There are no specific conditions that favour the formation of the orthic topsoils, but most of them were formed on northern slopes (n = 362). The south western slopes had the lowest number of orthic A horizons (n = 110).

5.3.2.4.6 Silicic soils

The dorbank B horizon was found only on the eastern slopes (Figure 5.39). It must be emphasized that only two observations of this horizon were made during the land type survey.

5.3.2.4.7 Calcic soils

The soft carbonate B horizon was noted on western, eastern, and north western slopes (Figure 5.39). Its organic carbon content ranged from 0.10% on western slopes to 0.69% on north western slopes. This horizon is also not very common in (n = 3). It is mostly formed under arid climates and Figure 5.39 shows that it was found in dry areas with an average aridity index of 0.20.

5.3.2.4.8 Duplex soils

Duplex soils were found within a wide range of slope aspects (Figure 5.39). The pedocutanic B horizons, found at the south western slopes, had the highest (0.78%) amount of organic carbon while those on the southern slopes had the lowest (0.51%). There was a significant difference in the organic carbon content of the pedocutanic B horizons on the eastern, north western, south eastern, north eastern, and south western slopes when compared to those on the southern slopes. Even though the difference was not significant, the organic carbon content at the northern slopes was not expected to be higher than at the southern slopes, because the cool wet conditions that prevail in southern slopes should promote accumulation of organic carbon by slowing down mineralisation by microorganisms (Tate, 1992a). On the other hand, the prismacutanic B horizons at the northern slopes had the highest organic carbon content of 0.53% and those on the north eastern slopes had the lowest of 0.35%. There was no significant difference in organic carbon content between the prismacutanic B horizons on the different slope aspects. Most of the prismacutanic B horizons developed on the western slopes (n = 39) while most of the pedocutanic B horizons were formed on the eastern slopes (n = 71).

5.3.2.4.9 Podzolic soils

Podzolic soils were found on the eastern, southern, western, and northern slopes (Figure 5.39). The highest organic carbon content of 2.88% was found on the northern slopes and the lowest of 0.53% on the eastern slopes. Due to the difference in climatic conditions the opposite was expected because decomposition of organic matter should be higher on northern slopes as they are warmer and drier than the eastern slopes. According to Tate (1992a) soil organic matter decomposition is faster in warm and dry environments. The difference in organic carbon content in the podzol B horizons on the eastern, southern, and western slopes was not significant but a significant difference was found between the eastern and northern slopes. Most of the podzol B horizons were reported at the southern slopes (n = 7).

5.3.2.4.10 Plinthic soils

The soft plinthic B horizons on the south western slopes had the highest organic carbon content of 0.52% and those at the western slopes had the lowest organic carbon content of 0.27% (Figure 5.40). The organic carbon content of the soft plinthic B horizons was not significantly different between the south western, south eastern, and northern slopes. These horizons on the western slopes had significantly lower organic carbon contents when compared to those on the slopes facing in north west, south, north, south east, and south west direction. Most of the soft plinthic B horizons were reported on northern slopes (n = 42). Since the soft plinthic B horizons require periodic saturation with water to be formed the southern slopes were expected to have the highest numbers of soft plinthic B horizons but only 36 were found on these slopes.

The hard plinthic B horizons were not as widely distributed as the soft plinthic B horizons (Figure 5.40). They were reported only on the south western, eastern, northern, and western slopes. In the hard plinthic B horizons the highest organic carbon content of 0.32% was found on the western slopes, while the lowest of 0.12% was on the south western slopes. There was no significant difference in organic carbon content between the hard plinthic B horizons noted at different slope aspects. The soft plinthic B horizons had the highest organic carbon content on the south western slopes while the hard plinthic B horizons had the lowest organic carbon content on the south western slopes. This shows that the behaviour of organic carbon was different in both plinthic B horizons. Even though not many hard plinthic B horizons were found, the northern slopes had three observations while the eastern and western slopes had two and the least number of observations was at the south western slopes with one horizon.

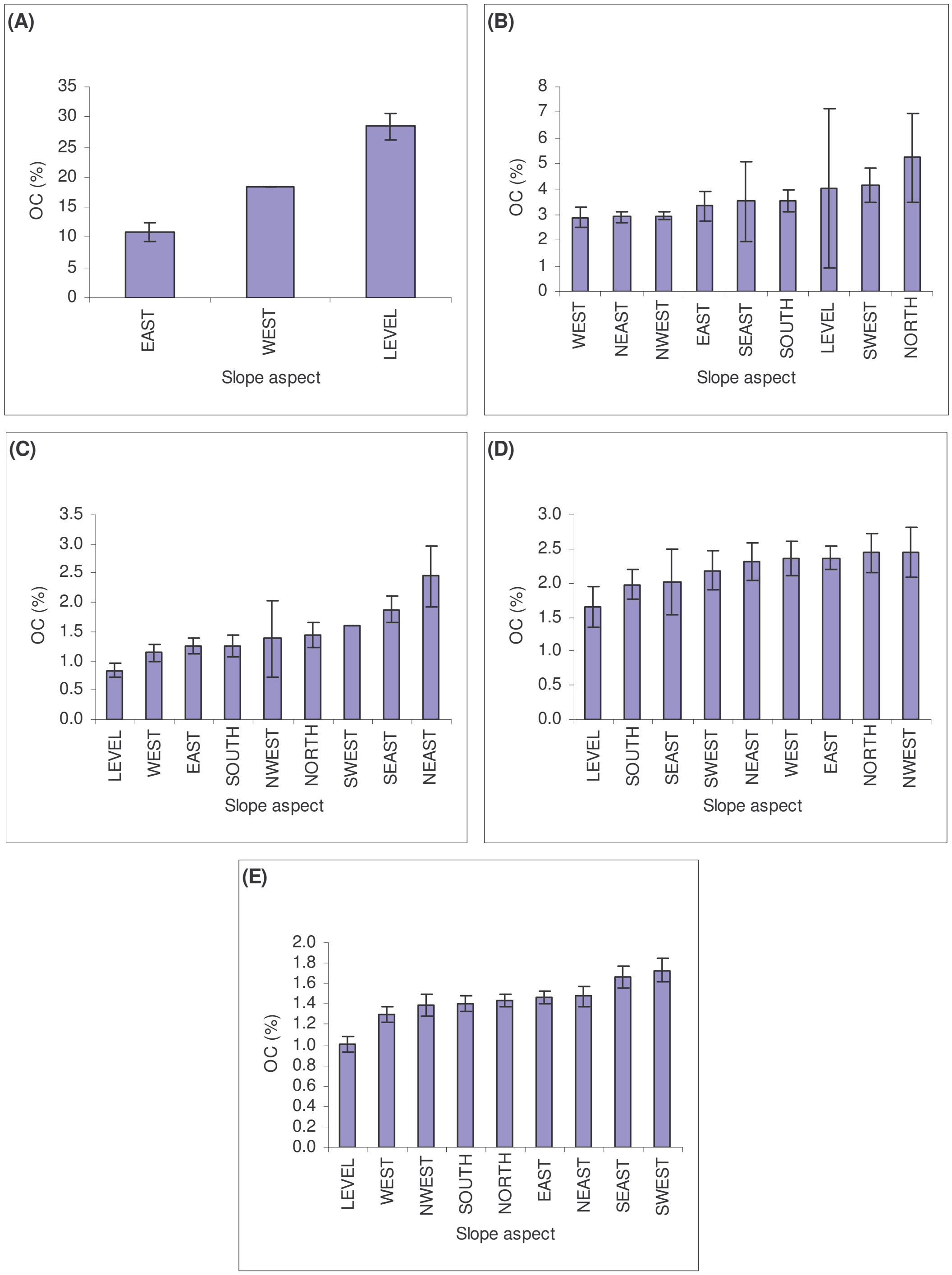


Figure 5.38 Effect of slope aspect on the organic carbon content of the diagnostic topsoil horizons: organic O (A), humic A (B), vertic A (C), melanic A (D), and orthic A (E)

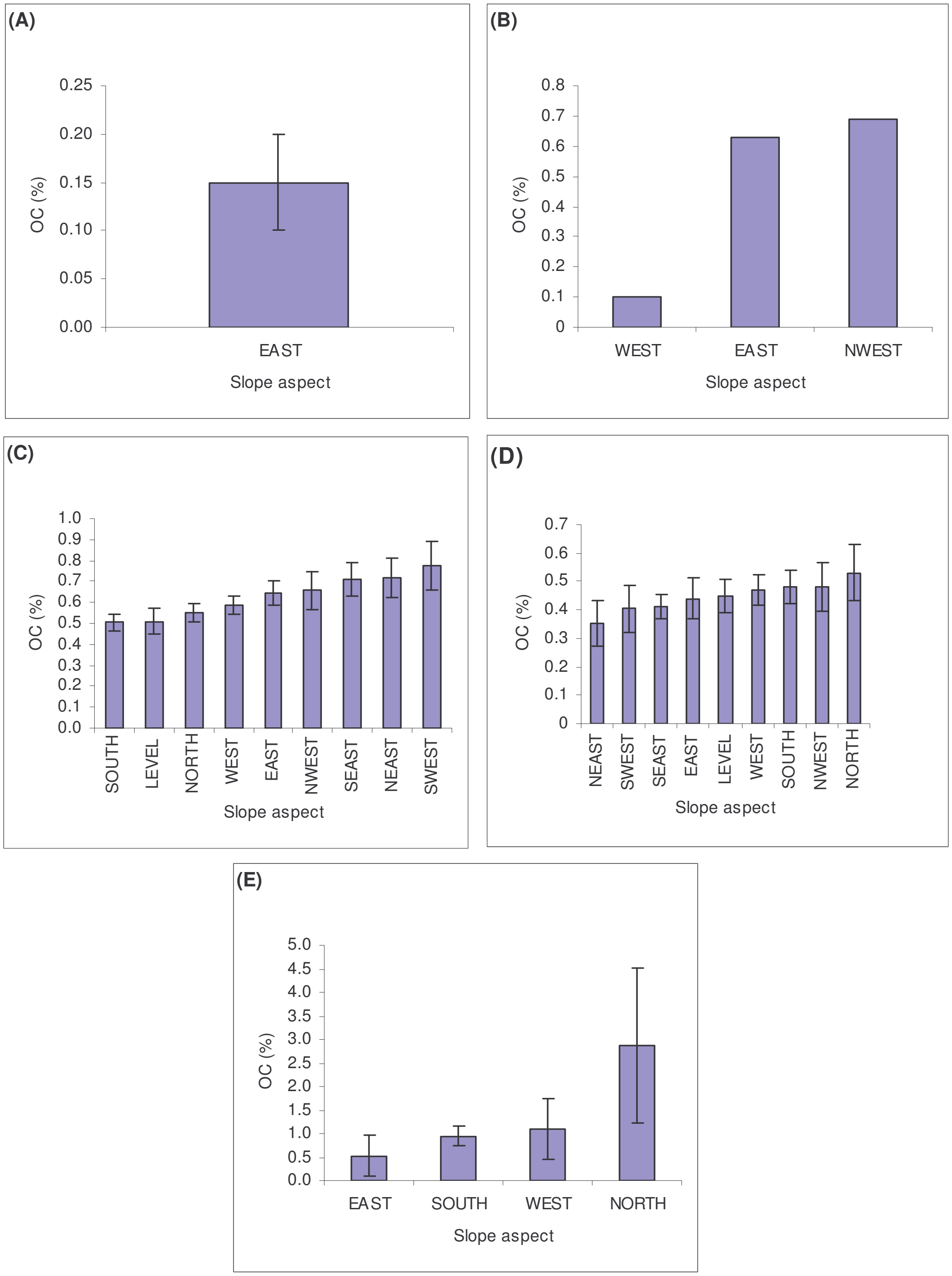


Figure 5.39 Effect of slope aspect on soil organic carbon content in the silicic soils: dorbank B (A), calcic soils: soft carbonate (B), duplex soils: pedocutanic B (C), prismacutanic B (D), and podzolic soils: podzol B (E)

5.3.2.4.11 Oxidic soils

The red apedal B was the most widely distributed horizon among the oxidic soils in relation to slope aspect, followed by the red structured B, and lastly the yellow-brown apedal B horizon (Figure 5.40). The highest organic carbon content in the red apedal B was found at the northern slopes (0.64%) and the lowest at the north western slopes (0.45%). The organic carbon content of the red apedal B horizons on the northern slopes was significantly higher than at the north western and level slopes. The organic carbon content of the red apedal B horizons on the northern slopes was expected to be lower than at the south and eastern slopes because of the higher rate of mineralisation on the northern slopes as they are warmer and drier. Warm temperatures and less soil water lead to low organic carbon contents (Lemenih & Itanna, 2004). However, the organic carbon content at the northern, south eastern, eastern, southern, south western, western, and north eastern slopes was not significantly different.

The yellow-brown apedal B horizons were reported on easterly, south easterly, and westerly slopes (Figure 5.40). In these horizons organic carbon content was highest (0.74%) on western slopes and lowest (0.47%) on eastern slopes.

The opposite was expected because in South Africa the westerly slopes are normally warmer and drier than the eastern slopes so the organic carbon was expected to be higher in the latter slopes. There was no significant difference in organic carbon between the eastern and western slopes. The variation in organic carbon data was high on the western slopes.

Organic carbon content of the red structured B horizons was highest on south western slopes (0.74%) and lowest on south eastern slopes (Figure 5.40). There was no significant difference in organic carbon content of red structured B horizons on the south west, level, and northern slopes. The organic carbon content of red structured B horizons on the southern slopes was significantly lower than on the other slope aspects except the western slopes. Most of the red structured B horizons were found on the northern slopes (n = 30) while only one was found on the south eastern slopes.

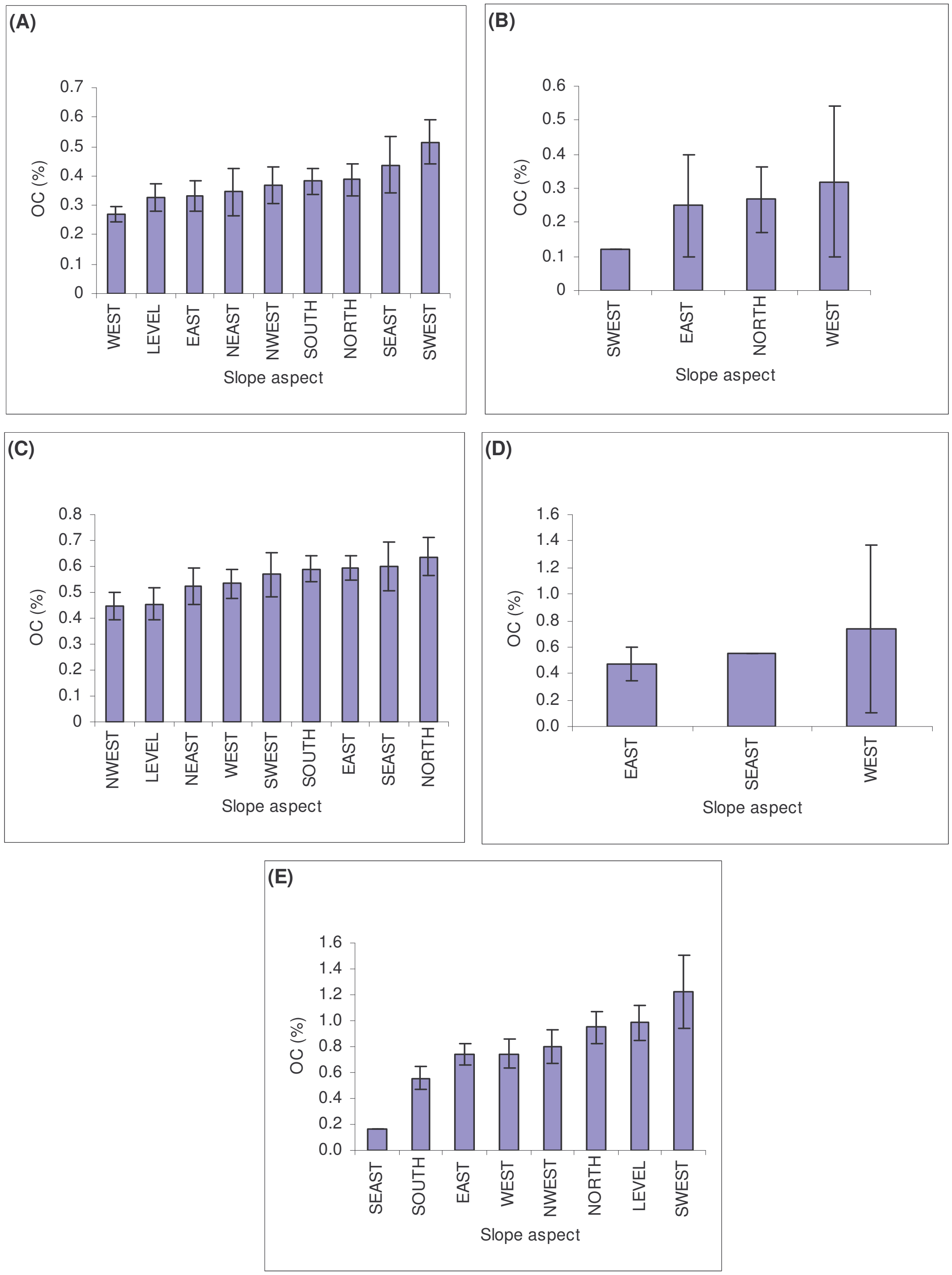


Figure 5.40 Effect of slope aspect on soil organic carbon content in the plinthic soils: soft plinthic B (A), hard plinthic B (B), and oxidic soils: red apedal B (C), yellow-brown apedal B (D), and red structured B (E)

5.3.2.4.12 Gley soils

As shown in Figure 5.41 the highest organic carbon content in the G horizons was recorded on the north west slopes (3.00%) and the lowest on level slopes (0.35%). Only one observation was done at the north west slopes so to reduce bias, the north east slopes provided the highest organic carbon content (0.82%) for comparison with the other slope aspects. The north western slopes probably accumulated more organic carbon because of a more favourable soil water regime that increased plant production (Entry *et al.,* 2002). The organic carbon content of the G horizons differed significantly between the north eastern, level, and south eastern slopes. Surprisingly most of the G horizons were observed on the northern slopes (n = 13) and not on the southern (n = 8) and eastern (n = 11) slopes. The formation of the G horizons requires periodic saturation with water so more of them were expected on the southern or eastern slopes as they are able to remain wet for longer, but probably the northern slopes received more rainfall and the soils were not well drained. The gleycutanic B horizons on the eastern slopes had the highest organic carbon content (Figure 5.41). There was no significant difference in organic carbon content of the gleycutanic B horizons of the different slope aspects, except for the south western and eastern slopes. Similar to the G horizon, most of the gleycutanic B horizons were reported on the northern slopes (n = 17).

The unconsolidated materials with signs of wetness were not very widely distributed as shown in Figure 5.41. These materials highest organic carbon content was on the south western slopes (0.44%) and the lowest on the level slopes (0.05%). On the other hand the unspecified material with signs of wetness recorded the highest organic carbon content on the level slopes (6.33%) and the lowest on the north western slopes (0.09%). The organic carbon data of unspecified material with signs of wetness at level slopes showed a lot of variation. The level slopes on which these materials occur promoted the accumulation of organic matter probably by providing unsuitable conditions for mineralisation. Water erosion on the upper slopes and wind erosion on the lower slopes can result in increased organic carbon contents on the level slopes (Gregorich *et al.,* 1998). Moges and Holden (2008) add that the effect of deposition on the lower slopes depends on the richness in nutrients of the material being deposited. Most of these horizons developed on the northern slopes.

5.3.2.4.13 Eluvial soils

The E horizons on the south eastern and north eastern slopes had the highest organic carbon content, namely 0.68% (Figure 5.41). However, E horizons on the south western slopes had the lowest organic carbon content (0.40%). The organic carbon content on the south eastern and north eastern slopes was significantly higher than on the northern, southern, level, and south western slopes. Thus the cool moist climate that is associated with the southern and eastern slopes influenced the organic carbon content of the E horizons positively. Cool moist conditions promote higher organic carbon levels because of reduced activity of microorganisms which play an important role in the mineralisation of organic matter (Sims & Nielsen, 1986; Tate, 1992a). Most of the E horizons were formed on eastern slopes (n = 53) probably because of the high water content needed for the leaching and reduction processes that occur during the formation of these horizons (Le Roux *et al.,* 1999).

5.3.2.4.14 Inceptic soils

The neocutanic B was found on a wide range of slope aspects (Figure 5.42). In this horizon organic carbon content was highest on north eastern (0.55%), southern (0.56%), and eastern slopes (0.56%) and lowest on western (0.34%) and south western (0.35%) slopes. The organic carbon content of the neocutanic B at the western, south western and north western slopes was significantly lower than at the south eastern, southern, and eastern slopes. The organic carbon content in regic sand was highest on eastern slopes (0.64%) and lowest on north western (0.45%) and western (0.46%) slopes (Figure 5.42). Regic sand shows a significant difference in organic carbon content when the north western and western slopes are compared to the level and eastern slopes. The stratified alluvium horizons on the eastern slopes had the highest (0.75%) and those on the western slopes had the lowest (0.27%) organic carbon content (Figure 5.42).

However, the difference in organic carbon content in the stratified alluvium was not significant between slope aspects. In all the inceptic soils of the cumulic sub-group the negative effect of dry and warm western slopes on organic carbon content was obvious. The highest levels of organic carbon were preserved in either the southern and/or western slopes which shows that the cool moist conditions associated with these slopes positively influenced carbon content.

As shown in Figure 5.43 the organic carbon content of lithocutanic B horizons on level slopes was the lowest (0.45%) and those on the south eastern slopes the highest (0.84%). The cool moist climate on the south eastern slopes probably promoted higher organic carbon content by not supporting biological activity (Sims & Nielsen, 1986). The organic carbon content of the lithocutanic B horizons on level slopes was significantly different from those on the northern, south western, western, north eastern, and eastern slopes.

There was, however, no significant difference in organic carbon content of these horizons found on the north western, southern, and south eastern slopes. The lithocutanic B horizons and the hard rock being inceptic soils of the lithic sub-group are signs of shallow soils. Their organic carbon content showed a similar pattern even though the hard rocks are not as widely distributed as the lithocutanic B (Figure 5.43). The lowest organic carbon content in hard rock was also found on the level slopes (0.22%) and the highest at south eastern slopes (0.57%). There was no significant difference in organic carbon content of the hard rock horizons found at different slope aspects. In both horizons the cool and moist conditions that characterize the south eastern slopes had a positive effect on the accumulation of organic carbon.

The lowest organic carbon content in unconsolidated material without signs of wetness (0.10%) and the unspecified dry material (0.11%) was on the south eastern slopes (Figure 5.43). The highest carbon content (0.53%) in the unconsolidated dry material was found on eastern slopes, but the difference in organic carbon content was not significant between slope aspects. However, the highest organic carbon content (0.42%) in the unspecified dry material was on north eastern slopes and this was significantly higher than the amount found on the south eastern and south western slopes (Figure 5.43).

The conditions on the south eastern slopes did not have a positive impact on the buildup of organic carbon in both materials. Conditions on the eastern and north eastern slopes had, however, a positive influence on the organic carbon content of these materials. In saprolite, on the contrary, the north eastern slopes recorded the lowest organic carbon content of 0.18% and the eastern slopes had a similar positive effect on organic carbon content (Figure 5.43). The organic carbon on the eastern slopes was significantly higher than at all other slope aspects where saprolites were found, except at the level and western slopes.

Slope aspect affected the organic carbon content in the diagnostic horizons and materials found in South Africa differently. According to Barry (2008) and Le Roux *et al.* (1999) in the southern hemisphere, for example in South Africa, the southern and eastern slopes are cooler and wetter than the northern and western slopes. The accumulation of soil organic carbon is favoured by a cool and moist climate as the conditions are not favourable for microbial activity.

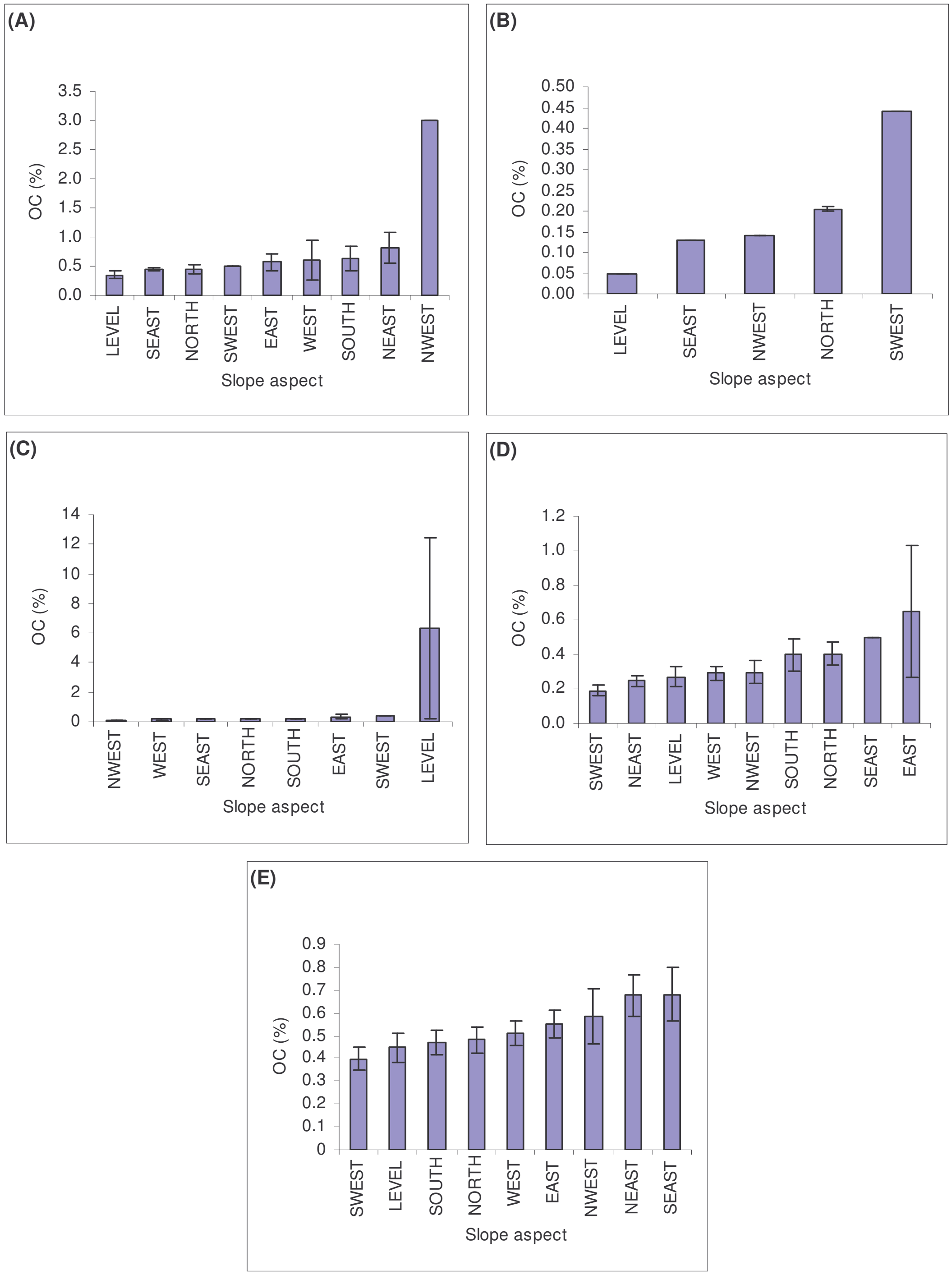


Figure 5.41 Effect of slope aspect on soil organic carbon in the gley soils: G horizon (A), unconsolidated material with signs of wetness (B), unspecified material with signs of wetness (C), gleycutanic B (D), and eluvial soils: E horizon (E)

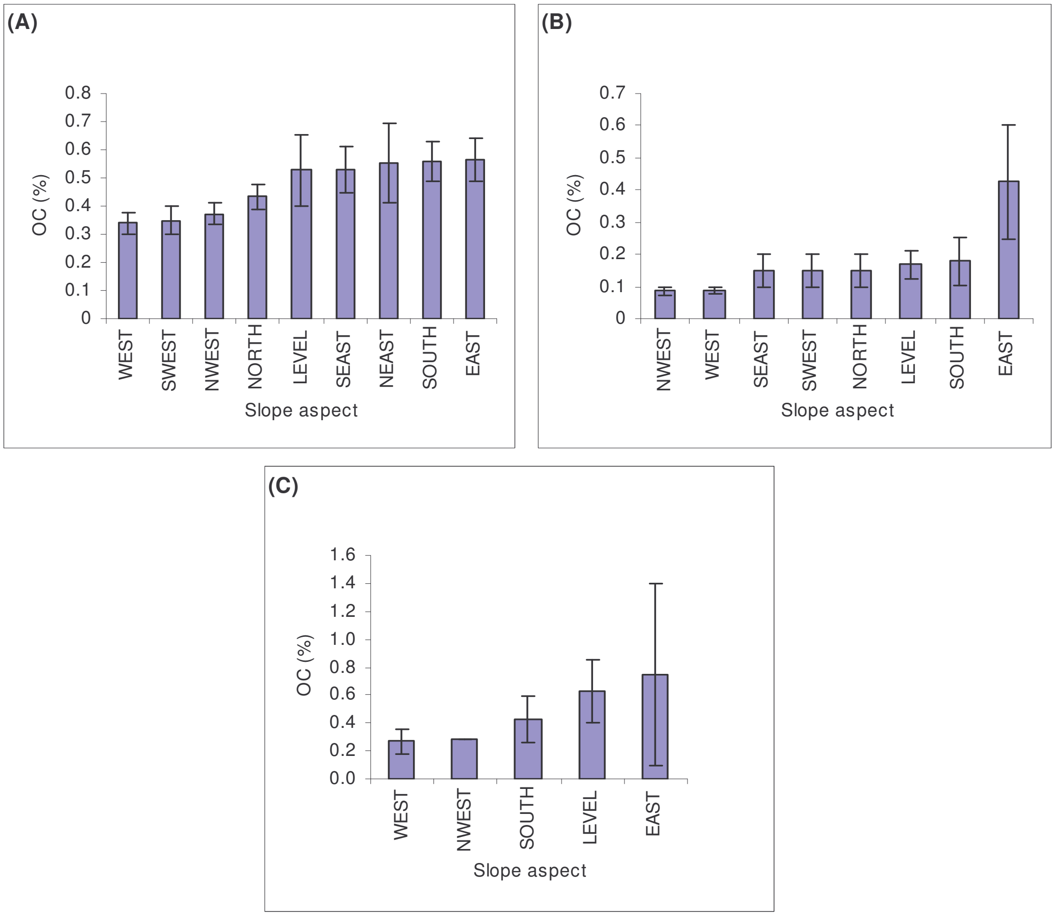


Figure 5.42 Effect of slopes type on soil organic carbon in the cumulic subgroup of the inceptic soils: neocutanic B (A), regic sand (B), and stratified alluvium (C)

Among all the diagnostic horizons and materials, the highest organic carbon content was observed in the organic O horizon (28.4%) on level slopes which allow for the accumulation of organic material especially in the presence of high vegetation cover. The highest organic carbon content in the unspecified material with signs of wetness was also noted on level slopes. Both southerly and easterly slopes had a positive influence on the accumulation of organic carbon in the dorbank, gleycutanic B, E horizon, neocutanic B, regic sand, stratified alluvium, lithocutanic B, hard rock, unconsolidated material without signs of wetness, and unspecified dry material. The northerly and westerly slopes favoured the accumulation of organic carbon in the humic A, melanic A, soft carbonate, prismacutanic B, podzol B, hard plinthic B, red apedal B, yellow-brown apedal B, and G horizons, as well as saprolite. The interaction of other soil forming factors and the different conditions in the slope aspects also influenced the formation of the different diagnostic horizons and materials. For example some were not as widely distributed as the others. The organic O, dorbank B, soft carbonate

B, podzol B, hard plinthic B, yellow-brown apedal B, unconsolidated material with signs of wetness and the stratified alluvium were found only on certain types of slopes.

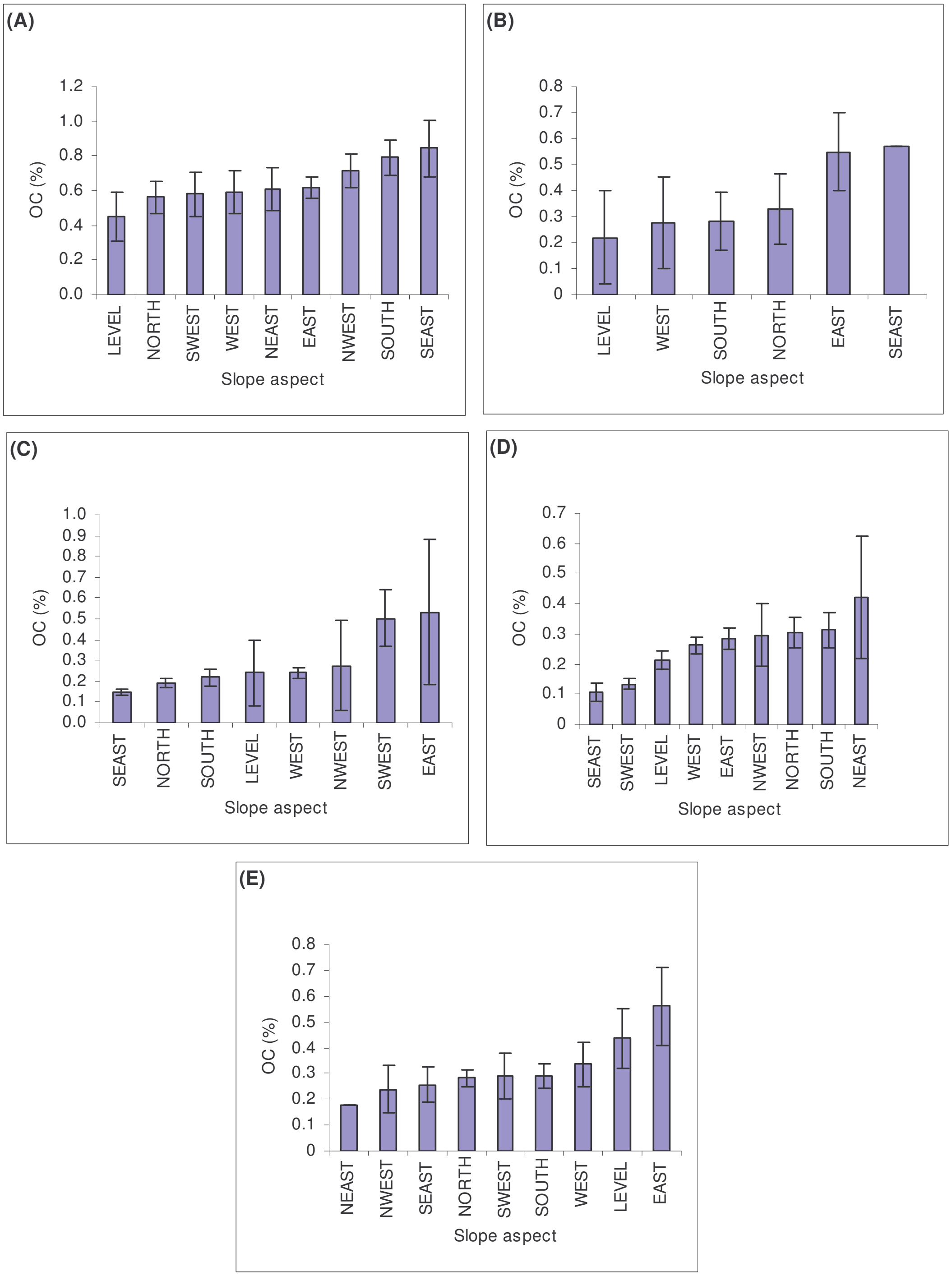


Figure 5.43 Effect of slopes type on soil organic carbon in the lithic subgroup of the inceptic soils: lithocutanic B (A), hard rock (B), unconsolidated material without signs of wetness (C), unspecified dry material (D), and saprolite (E)

5.3.3 Clay content

Among all the other soil physical properties clay content was highlighted because it shields soil organic carbon from decomposition (Anderson *et al.,* 1981). Spain (1990) and Jobbagy and Jackson (2000) reported that higher organic carbon levels were associated with high clay content. The amount of clay in the soils also determines the rate at which the soil can retain nutrients. In this section the correlation of clay and organic carbon in diagnostic horizons is examined as shown in Figures 5.44 to 5.49.

5.3.3.1 Organic soils

The correlation between clay and organic carbon in the organic O topsoil was better than in the other topsoils with a correlation coefficient of 0.43 (Figure 5.44). However, about 57% of the variation in data could not be accounted for. The relationship between clay and organic carbon in this horizon was negative. Expectations were that the higher the clay content the higher the amount of organic carbon, because of the high cation exchange capacity associated with clay as well as the adherence of organic matter to clay particles preventing its mineralisation (Burke *et al*., 1989).

5.3.3.2 Humic soils

There was a very poor relationship between organic carbon and clay content in the humic A horizon with a correlation coefficient of 0.01 (Figure 5.44). Even though the correlation was very weak, the relationship between organic carbon content and clay content in this horizon was positive.

5.3.3.3 Vertic soils

Organic carbon and clay also has a poor relationship in the vertic topsoils (Figure 5.44). Only 15% of the variation could be explained. The relationship between organic carbon and clay was negative. Vertic topsoils normally have a high clay content (Soil Classification Working Group, 1991). Soils with high clay content are associated with waterlogging and anaerobic conditions that normally favour the accumulation of organic matter (White, 2006). An increase in clay content in this horizon was therefore expected to result in an increase in organic carbon content, which did not happen (Tate, 1992a).

5.3.3.4 Melanic soils

The correlation between organic carbon and clay was very weak with a correlation coefficient of 0.02 (Figure 5.44). Even though the relationship was weak, an increase in clay content resulted in an increase in organic carbon content.

5.3.3.5 Orthic soils

Only 29% of the variation could be clarified by the data in the orthic A topsoil (Figure 5.44). The correlation coefficient value was unfortunately too low for any conclusions to be drawn. Organic carbon and clay had a positive relationship in this horizon. Due to a wide range of conditions in which these topsoils were formed their organic carbon content varies. However, an increase in clay content contributed positively to the accumulation of organic carbon.

5.3.3.6 Silicic soils

The dorbank B horizon had the lowest number of observations (n = 2) among all the diagnostic horizons (Figure 5.45). This affected the correlation between organic carbon and clay content in this horizon which was very high (R^2 = 1; Figure 5.43). No conclusions can be made therefore on this relationship which was positive.

5.3.3.7 Calcic soils

A better correlation coefficient of 0.58 was obtained between organic carbon and clay in the soft carbonate B horizon (Figure 5.45). This horizon was also not very common in the land type survey data since only three observations were reported. Organic carbon and clay had a negative relationship in this horizon.

5.3.3.8 Duplex soils

The relationship between organic carbon and clay was very poor in the duplex soils with a correlation coefficient of 0.04 for the pedocutanic B horizon and 0.05 for the prismacutanic B horizon (Figure 5.45). These horizons are associated with high accumulations of clay (Fey, 2009). The positive relationship between organic carbon and clay was expected in this horizon since the poor drainage conditions that are associated with clayey soils produce unsuitable conditions for the mineralisation of organic matter by hindering microbial action (White, 2006) and also because clay protects organic matter against degradation.

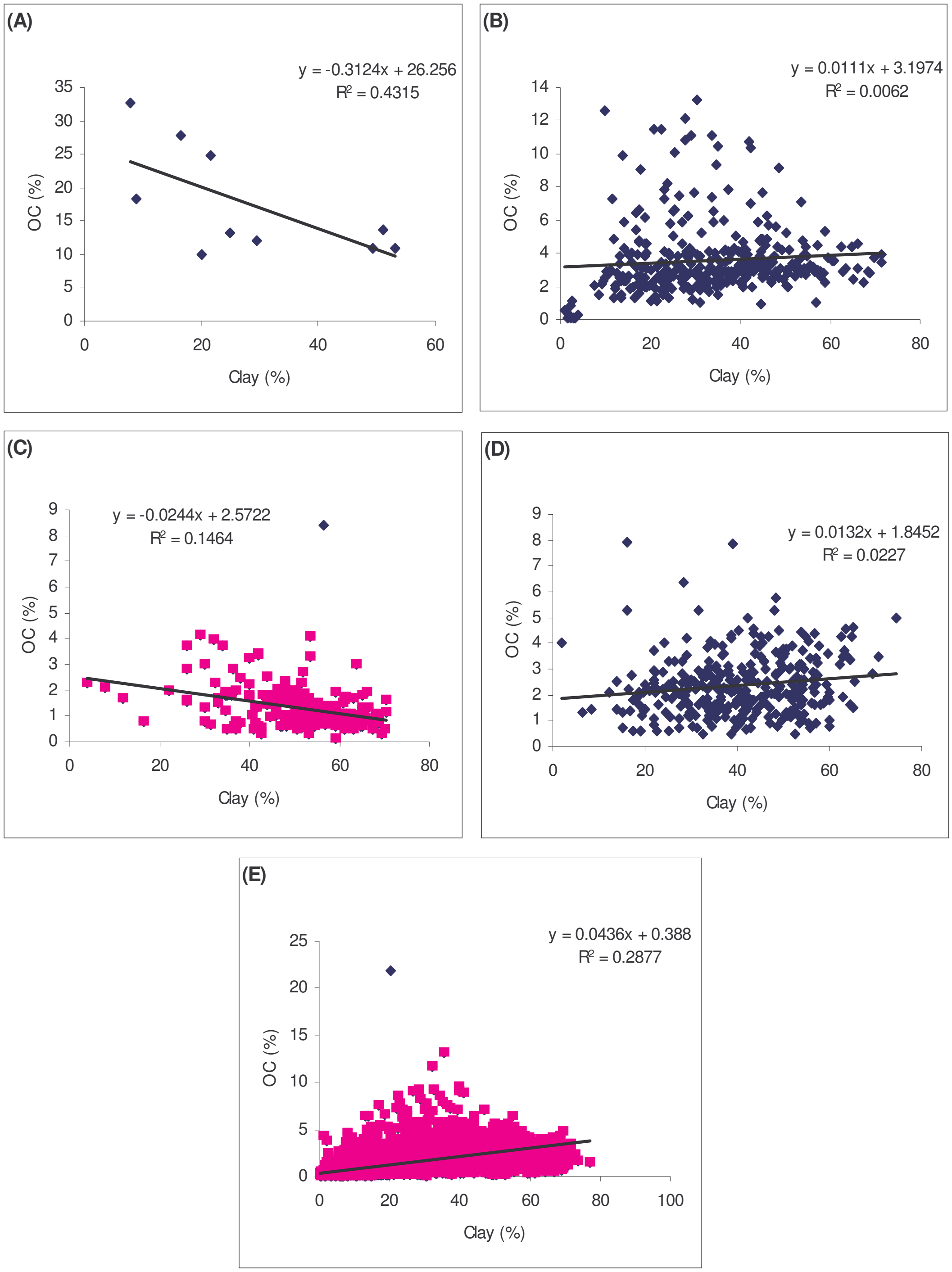


Figure 5.44 Effect of clay content on organic carbon content in the diagnostic topsoil horizons: organic O (A), humic A (B), vertic A (C), melanic A (D), and orthic A (E)

5.3.3.9 Podzolic soils

A very low correlation coefficient of 0.01 was found between organic carbon and clay in the podzol B horizon (Figure 5.45). Even though the relationship was very poor an increase in clay resulted in an increase in organic carbon. The podzolic soils are characterised with a low average clay content of only 9%.

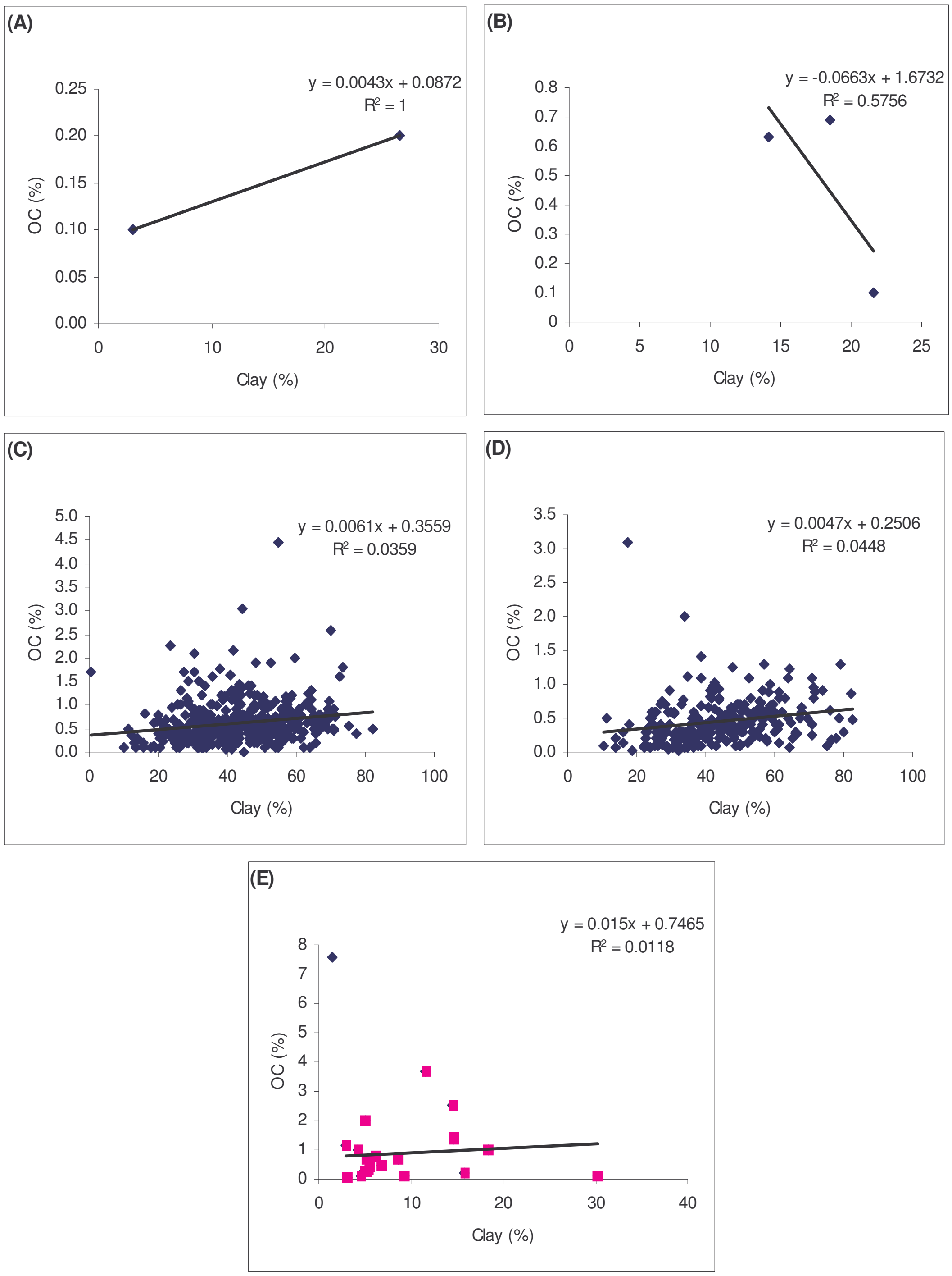


Figure 5.45 Effect of clay content on the organic carbon content in the silicic soils: dorbank B (A), calcic soils: soft carbonate (B), duplex soils: pedocutanic B (C), prismacutanic B (D), and podzolic soils: podzol B (E)

5.3.3.10 Plinthic soils

Very low correlation coefficients were recorded between organic carbon and clay in the soft (0.05) and hard (0.03) plinthic B horizons (Figure 5.46). The average clay content for the soft plinthic B horizons (30%) was slightly higher than for the hard plinthic B horizons (25%). The relationship between organic carbon and clay was positive in the soft plinthic B horizons but negative in the hard plinthic B horizons. These two horizons were expected to behave in the same manner since they can both be associated with fluctuating water tables and the hard plinthic B horizon is a mature version of the soft plinthic B horizon (Fey, 2009).

5.3.3.11 Oxidic soils

Organic carbon and clay are poorly related in the oxidic soils with correlation coefficients of 0.20, 0.18 and 0.12 for the red apedal B, yellow-brown apedal B, and red structured B horizons respectively (Figure 5.46). The average clay content was 26% for the yellow-brown apedal B, 33% for the red apedal B, and 54% for the red structured B. Organic carbon and clay had a positive relationship in these horizons. Even though the red structured B had the highest average clay content it had the lowest correlation coefficient.

5.3.3.12 Gley soils

The relationship between organic carbon and clay was very weak in all the gley soils (Figure 5.47). Correlation coefficients ranged from 0.01 in the G horizon and unconsolidated material with signs of wetness to 0.04 in the unspecified material with signs of wetness and 0.05 in the gleycutanic B horizon. Organic carbon and clay had a positive relationship in these horizons except in the G horizon which was negative.

5.3.3.13 Eluvial soils

A positive relationship between organic carbon and clay was established in the E horizon (Figure 5.47). A low correlation coefficient of 0.28 was calculated. The E horizons are characterised with a low average clay content, namely 14% probably because of the high rate of eluviation and leaching processes that occur as prerequisites for their formation.

5.3.3.14 Inceptic soils

Among the cumulic subgroup of the inceptic soils, organic carbon and clay correlated better in the stratified alluvium with a correlation coefficient of 0.24 (Figure 5.48). These two parameters correlated very poorly in the neocutanic B and regic sand horizons with correlation coefficients of 0.09 and 0.05 respectively. The regic sand and stratified alluvium horizons both had an average clay content of 15%, while the neocutanic B had an average clay content of 26%. In all these horizons organic carbon and clay showed a positive relationship.

As displayed in Figure 5.49 the correlation of organic carbon and clay decreased in the following pattern in the inceptic soils of the lithic subgroup: hard rock (R^2 = 0.13), unspecified dry material (R^2 = 0.10), unconsolidated material with signs of wetness (R^2 = 0.10), saprolite (R^2 = 0.09), and lithocutanic B (R^2 = 0.01). The relationship was positive for all members of the lithic subgroup but unfortunately it was poor.

The correlation between organic carbon and clay was very poor in most of the diagnostic horizons and materials. Sims and Nielsen (1986) also found that the correlation between organic carbon and clay was very low with their correlation of determination (r) values ranging from -0.19 to 0.12. The correlation coefficient values found in this study ranged from 0.01 to 0.28. Exceptions were the organic O (R^2 = 0.43), dorbank B (R^2 = 1), and soft carbonate B (R^2 = 0.58) horizons which yielded better correlations. The low number of observations contributed to high correlation coefficients in the dorbank B (n = 2), and the soft carbonate B (n = 3) horizons. Hontoria *et al.* (1999) found also that the correlation between organic carbon and clay content was not significant. They argued that this was probably caused by a diversity of parent materials found in their study area that interferes with the effect of soil texture on soil organic carbon. Similarly, Kadeba (1977) established that the effect of soil texture on the levels of soil organic carbon depends on the parent material of the soils.

Organic carbon and clay showed a positive relationship in most diagnostic horizons and materials except in the organic O, vertic A, soft carbonate B, hard plinthic B, and G horizons. Jobbagy and Jackson (2000) also stated that an increase in clay content resulted in an increase in organic carbon content. Spain (1990) reported that clay content and organic carbon were positively related except in soils with a basaltic origin, which was negative. So probably the parent material of the soils that gave a negative relationship had a great impact on the results.

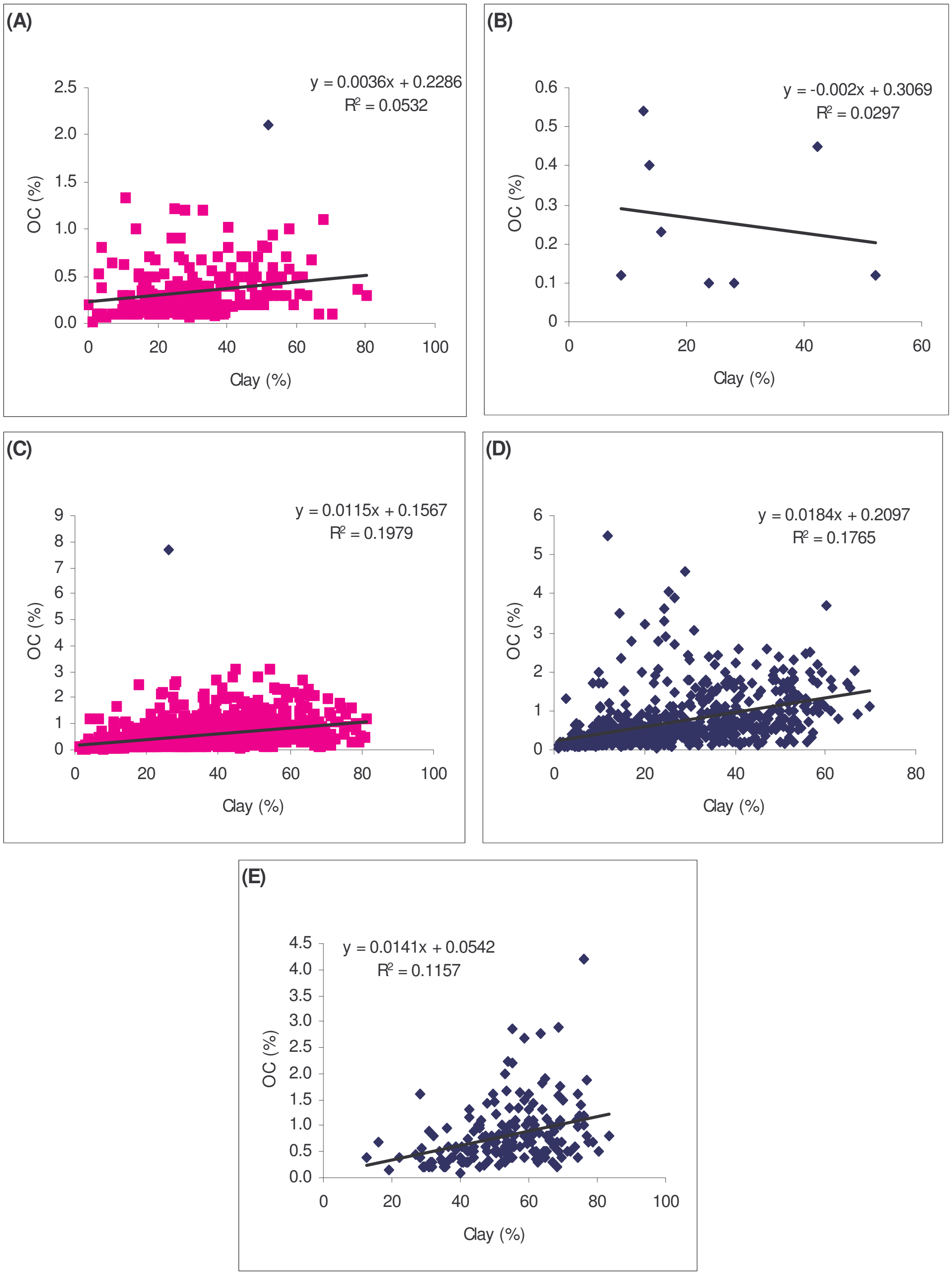


Figure 5.46 Effect of clay content on soil organic carbon content in the plinthic soils: soft plinthic B (A), hard plinthic B (B), and oxidic soils: red apedal B (C), yellow-brown apedal B (D), and red structured B (E)

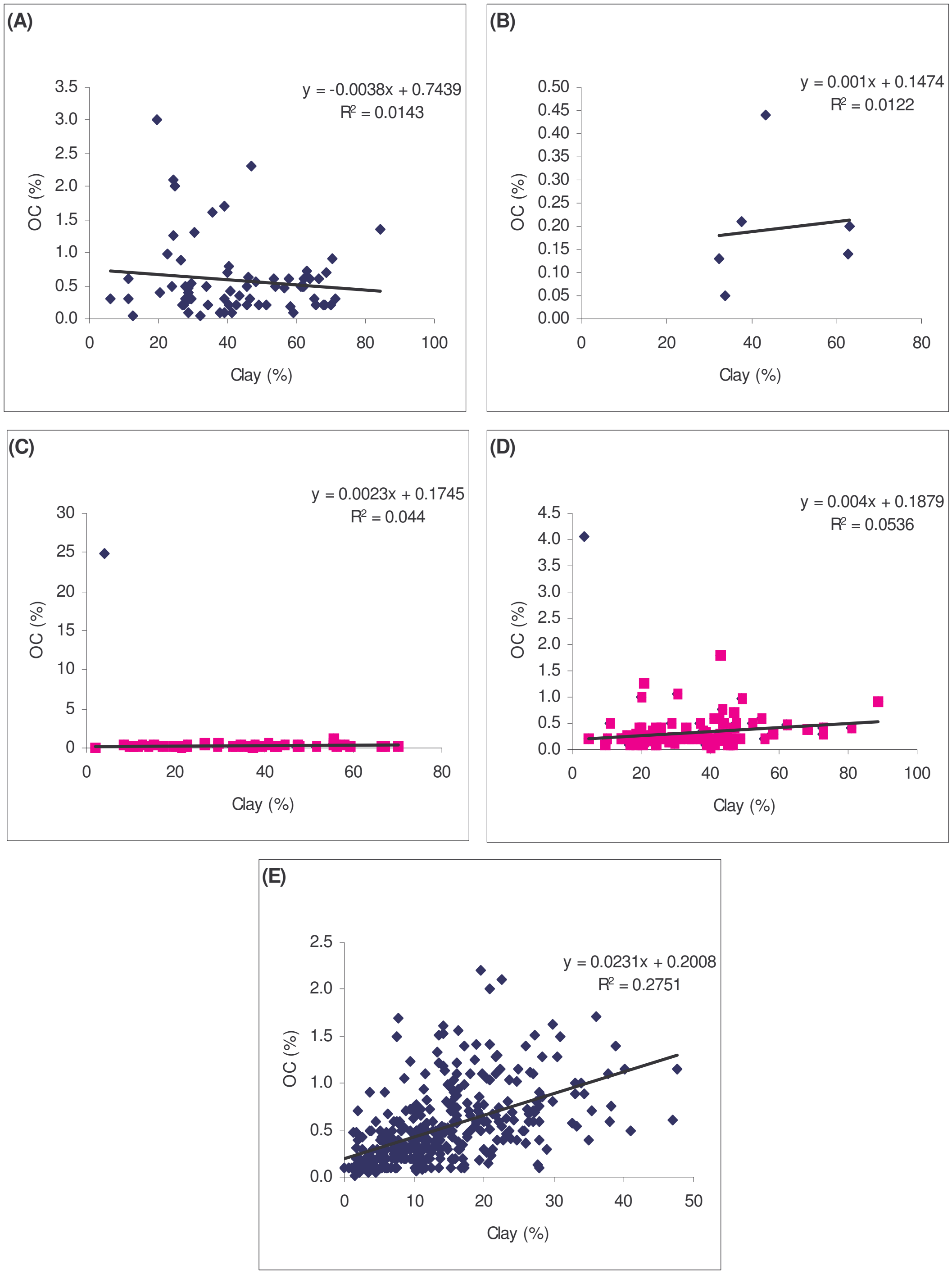


Figure 5.47 Effect of clay content on soil organic carbon in the gley soils: G horizon (A), unconsolidated material with signs of wetness (B), unspecified material with signs of wetness (C), gleycutanic B (D), and eluvial soils: E horizon (E)

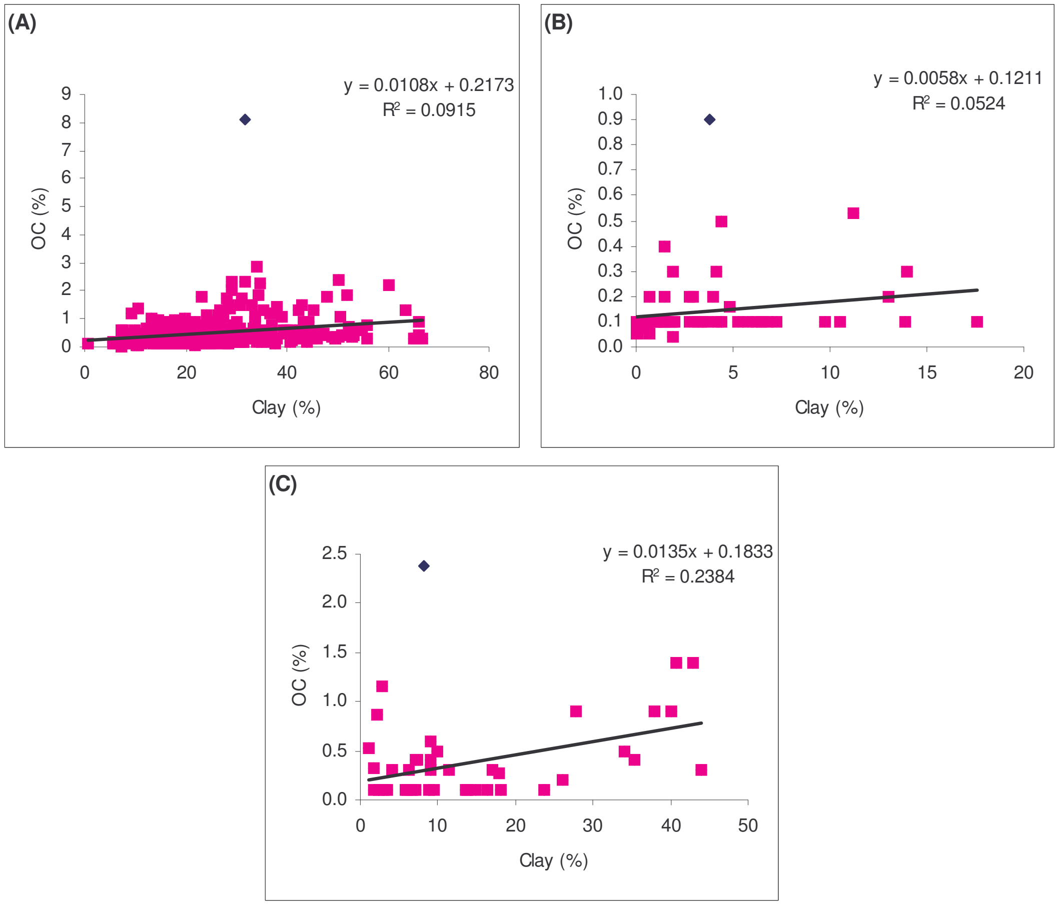


Figure 5.48 Effect of clay content on soil organic carbon in the cumulic subgroup of the inceptic soils: neocutanic B (A), regic sand (B), and stratified alluvium (C)

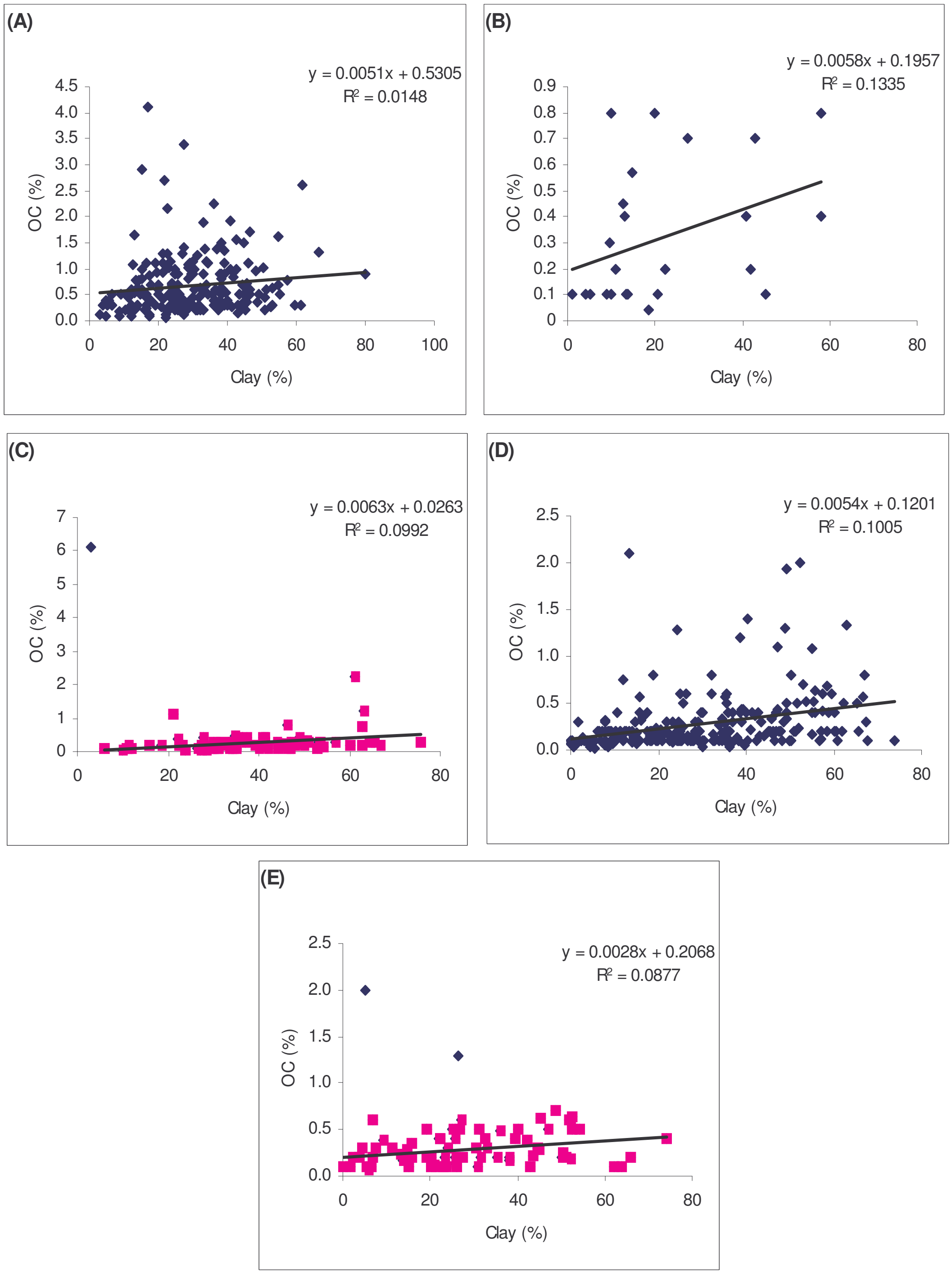


Figure 5.49 Effect of clay content on soil organic carbon in the lithic subgroup of the inceptic soils: lithocutanic B (A), hard rock (B), unconsolidated material without signs of wetness (C), unspecified dry material (D), and saprolite (E)

5.3.4 Estimating soil organic carbon in diagnostic soil horizons and materials

The effect of environmental conditions on the levels of soil organic carbon in the diagnostic soil horizons and materials was estimated by computing models that were developed using Microsoft Excel (2003). All the countable variables that play a vital role in soil formation, especially those available in the land type survey database were used. The variables included climate (evaporation, rainfall, and aridity index), topography (slope percentage and slope aspect), and soil texture (clay).

The diagnostic horizons and materials were divided into soil groups (Table 5.1). After determining the correlation of the different variables to organic carbon individually in the previous steps, the variables were combined and a regression was done to determine any improvements from the previous results. All the data points with missing data were deleted. During the development of the model, the variables with a coefficient greater than 0.01 were added to the model.

The correlation coefficient values of the diagnostic horizons and materials ranged from 0.02 in the cumulic soils of the lithic sub-group (the unconsolidated material without signs of wetness, unspecified dry material and the saprolite) to 1 in the organic, silicic and calcic soils (Table 5.4). A low number of observations in the silicic (n = 2) and calcic (n = 3) soils contributed to the high correlation coefficients in those soils. The higher the numbers of observations the closer the results are in representing the mean of the entire population (Cumming *et al.,* 2007). In the organic O horizon, the clay content contributed significantly to the model and resulted in a high correlation coefficient of 0.43 (Section 5.3.3.1). The addition of other variables in a regression, even though it was not significant, resulted in correlation coefficient of 1. The correlation coefficient for the podzolic soils also improved to 0.75 with all the variables contributing to the model. In all the remaining diagnostic horizons the use of all the variables together to compute models that could be used to estimate organic carbon did not produce acceptable correlation coefficients (Hoshmand, 1998).

According to Table 5.4 aridity index (X_3) seemed to affect the amount of organic carbon in soil by appearing 13 times followed by clay content (X_4) and slope percentage (X_5) appearing 7 and 4 times respectively. Unfortunately, the use of all the numeric variables failed to improve the relationship with organic carbon to an acceptable level, except for the organic podzolic soils.

Table 5.4 Estimating soil organic carbon in the diagnostic soil horizons and materials

Soil groups		Correlation coefficient (R^2)	Count (n)	Model
Organic		1.00	4	$Y = -6.77 \times 10^{16} - 0.62X_4$
Humic		0.18	73	$Y = -10.96 + 16.86X_3 + 0.04X_5$
Vertic		0.45	108	$Y = 3.2 + 4.16X_3 - 0.03X_4 - 0.13X_5$
Melanic		0.40	164	$Y = 4.24 + 3.76X_3 + 0.01X_4$
Orthic		0.46	2810	$Y = -0.41 + 6.55X_3 + 0.03X_4$
Silicic		1.00	2	$Y = 1.42 - 0.001X_2$
Calcic		1.00	3	$Y = -2.01 + 0.001X_2$
Duplex		0.12	704	$Y = 0.24 + 0.55X_3$
Podzolic		0.75	29	$Y = -50.22 - 0.04X_1 + 0.03X_2 + 68.80X_3$ $0.06X_4 - 0.02X_5$
Plinthic		0.08	274	$Y = -0.1 + 0.58X_3$
Oxidic		0.27	1677	$Y = -0.06 + 2.29X_3$
Gley		0.05	193	$Y = 2.33 - 10X_3 - 0.02X_4 - 0.03X_5$
Eluvial		0.36	355	$Y = 0.26 + 2.06X_3 + 0.02X_4$
Inceptic	Cumulic	0.27	375	$Y = 1.09 + 0.60X_3$
	Lithic	0.19	218	$Y = 2.54 - 3.45X_3$
Underlying material		0.02	396	$Y = 0.31 - 1.07X_3$

Where: Y = Carbon percentage

X_1 = Rainfall

X_2 = Evaporation

X_3 = Aridity index (AI)

X_4 = Clay percentage

X_5 = Slope percentage

X_6 = Slope aspect

5.4 Conclusions

The diagnostic topsoil horizons proved to have the highest organic carbon content, ranging from an average of 1.41% to 20.89% when compared to the diagnostic subsoil horizons which range from 0.15% to 1.18%. The amount of organic carbon in these soils may be a result of the interaction of several soil forming factors such as climate (rainfall and temperature), topography (terrain morphology, slope percentage, and slope aspect), as well as the texture of the soil (clay content). The exploration of the relationship between organic carbon content and the indices of climate namely: rainfall, evaporation, and aridity index was very poor for all the diagnostic topsoil and subsoil horizons, except the relationship between organic carbon and evaporation in the organic O horizon which was very good (R^2 = 0.92). As a result of a low number of observations the silicic and the calcic soils also had very high correlations between organic carbon and rainfall, evaporation, and aridity index. The relationship was positive in some diagnostic horizons while it was negative in others. Unfortunately, because of the low correlation coefficient values (with a few exceptions) that are dominating in the results, the effect of rainfall, evaporation, and aridity index was not conclusive.

The effect of topography on the formation of certain horizons was obvious since some of them were limited to certain areas in the landscape. For example the yellow-brown apedal B horizons were restricted to the valley bottom only. Therefore the different conditions that are found in different parts of the landscape influence the types of soils found there depending on the prerequisites for their formation.

The slope percentage had an effect on the organic carbon content in some diagnostic horizons and material by influencing their soil water regime. The amount of water that can be held by the soil affects the accumulation of soil organic carbon by controlling the vegetative growth and hence the activities of the soil microorganisms that are responsible for the formation and decomposition of soil organic carbon. Slope percentage also affected the formation of the different soils where some of the diagnostic horizons were restricted to lower slope areas while others are widely distributed throughout the landscape. Slope aspect was also very important. The cool and moist climatic conditions on the south easterly slopes were expected to favour the accumulation of organic carbon in South African soils. But this was not the case in some soils where the highest organic carbon content was recorded for example on warm and dry northerly slopes. Depending on the diagnostic horizon the aspect of the slopes had different effects on the organic carbon content.

The correlation between organic carbon and clay was very poor in most of the diagnostic horizons and materials. The combination of all the variables improved the correlation coefficients of some horizons for example the organic O (R^2 = 0.51), dorbank B (R^2 = 1.00), and soft carbonate B (R^2 = 0.58) horizons.

Multiple regression models with varying combinations of rainfall, evaporation, aridity index, clay, slope percentage, and slope aspect could explain 2% to 100% variability of organic carbon in the diagnostic horizons. The highest correlations were in the organic O topsoil, and the silicic and calcic subsoils. Unfortunately, they were based on low sample numbers therefore regression equations from these correlations are not significant. Probably the addition of other soil forming factors such as parent material as well as the addition of temperature to the model may add value to the regression models.

CHAPTER 6
ORGANIC CARBON CONTENT IN THE SOIL FORMS OF SOUTH AFRICA

6.1 Introduction

The classification of soils in the Binomial Soil Classification System for South Africa was made up of two categories namely: soil forms and soils series, the former being the upper and the latter the lower taxon (MacVicar *et al*., 1977). During the development of the Taxonomical Soil Classification System for South Africa the soil series category was removed, the soil family was introduced and was now used as the lower category (Soil Classification Working Group, 1991). In both classification systems each soil form is characterised by a unique sequence of diagnostic horizons and materials (Laker, 2003). However, classification of soils starts with the demarcation of master horizons, followed by the designation of the diagnostic horizons and materials.

A number of processes and factors can lead to the formation of different diagnostic horizons and materials. These processes are governed by the factors of soil formation: climate, time, parent material, vegetation, and topography (Jenny, 1941). Scotney and Dijkhuis (1990) stated that South African soils have different characteristics which were caused by the interaction of several processes such as weathering and the factors of soil formation. These factors affect the formation of the diagnostic horizons and materials that make up the soil forms by influencing the soil water regime, local climate, and the vegetation of the area (White, 2006). A soil form can consist of up to three or more diagnostic horizons and materials situated at varying depths in a profile (Soil Classification Working Group, 1991). Organic carbon content, base status, plasticity index, wetness, colour, and texture are some of the properties used for distinguishing the different diagnostic horizons and materials for the soil forms (Soil Classification Working Group, 1991). Therefore studying the behaviour and placement of the diagnostic horizons and materials that give rise to these soils will give a broad understanding on the diverse nature of South African soils.

Recent studies revealed that the fertility status of South African soils has declined throughout the years due to increased activities such as cultivation, overgrazing, and deforestation, all of which result in declining organic carbon levels (Prinsloo *et al*., 1990; Du Preez & Snyman, 1993; Van Zyl & Du Preez, 1997; Lobe *et al*., 2001). Sims and Nielsen (1983) reported that the organic carbon content of soil decreases as the depth of the soil increases. Furthermore, Barnard (2000) reported that the organic carbon distribution was higher and more obvious in the topsoils than in the subsoils where it becomes less defined. Earlier results of this study also portrayed the same pattern where the diagnostic topsoils had higher organic carbon content than the diagnostic subsoil horizons and underlying materials. The Soil Classification Working Group (1991) stated that soils should be dealt with as a whole. Therefore after studying the organic carbon content in the master horizons (Chapter 4) and in the diagnostic horizons and materials (Chapter 5), the organic carbon content in the different soil forms is dealt with in this chapter as well as the materials that characterise each soil form.

6.2 Procedure

A total of 60 soil forms was described in the land type survey. This survey started in 1970 and a large number of modal soil profiles was analysed for physical and chemical properties (Land Type Survey Staff, 2003). The diagnostic horizons and materials that characterise the different soil forms are given in Table 3.5. Data points with zero organic carbon and those with missing organic carbon data were deleted from the database.

Based on the Binomial Soil Classification System for South Africa (MacVicar *et al.,* 1977), which was used for the land type survey and the Taxonomical Soil Classification System for South Africa (Soil Classification Working Group, 1991) the gaps where diagnostic horizon designation was missing, were filled. Reference to the soil forms was done for the classification of the diagnostic horizons. For consistency a list of underlying materials as displayed in Table 3.4 was compiled to help fill these gaps.

According to MacVicar *et al.* (1977) and the Soil Classification Working Group (1991), the organic O topsoil must have at least an organic carbon content of 10% therefore all the soil forms with diagnostic topsoils that have an organic carbon content of less than 9%, but were classified as organic O were deleted from the database.

The dominant topsoil horizons and their number of observations in some instances were used as criteria to choose which soil forms would be used to study the amount of organic carbon in the soils of South Africa. For soil forms with humic, melanic, and orthic A horizons, only those with respectively more than 90, 100, and 200 observations were chosen. Since only one soil form had an organic O topsoil and only two soil forms have vertic A topsoils and all three of them were included, regardless of their number of observations. This selection resulted in a total of 17 soil forms (Table 6.1). Table 6.2 shows the diagnostic horizons and materials of these soil forms.

Table 6.1 Soil forms selected for the study according to their dominant topsoil horizon (Soil Classification Working Group, 1991)

Topsoil	Soil forms	Designations	Count (n)
Organic O	Champagne	Ch	13
Humic A	Inanda	Ia	113
	Nomanci	No	98
Vertic A	Arcadia	Ar	161
	Rensburg	Rg	59
Melanic A	Mayo	My	159
	Bonheim	Bo	135
Orthic A	Avalon	Av	242
	Cartref	Cf	202
	Clovelly	Cv	560
	Glenrosa	Gs	412
	Hutton	Hu	1290
	Mispah	Ms	271
	Oakleaf	Oa	381
	Shortlands	Sd	202
	Swartland	Sw	224
	Valsriver	Va	264

Some statistical calculations were done per diagnostic horizon or material in each of the 17 selected soil forms using Microsoft Excel (2003). Depending on the number of subsoils per soil form, the range, 25th percentile, median, 75th percentile, mean, and standard error of the organic carbon content were calculated. Some soil forms like the Clovelly, Glenrosa, Hutton, Oakleaf, Shortlands, Swartland, and Avalon had more than three subsoils. The standard error bars were used to test significance of difference as suggested by Cumming *et al.* (2007) which showed that the overlapping of the standard error bars meant the horizons or materials were significantly different from each other or *vice versa.* They also state that the amount of variation in the data is revealed by the length of the error bars.

6.3 Results and discussion

The calculated statistics for organic carbon (range, 25th percentile, median, 75th percentile, mean, and standard error) per diagnostic horizon or material in each of the selected soil forms are given in Table 6.2. However, only the organic carbon content in the topsoil and first subsoil horizons were explored in every soil form. This decision is based mainly on the fact that soil organic carbon decreases with depth (Oades, 1995). In addition it seems that there is some disagreement on the depth to which a horizon or material can be regarded as being diagnostic. The Soil Classification Working Group (1991) stated that a horizon is diagnostic only if it appears within 1500 mm from the soil surface and sometimes the third horizon may occur within or below the 1500 mm depth. Laker (2003) argues that a diagnostic horizon should be considered in classification only if it appears within the 1200 mm depth, based on the fact that a normal soil auger is only 1200 mm in length.

6.3.1 Soil forms with organic O topsoils

The Champagne soil form is the only soil form in South Africa that has an organic O topsoil. The underlying material is the unspecified material with signs of wetness (Figure 6.1). A significantly high organic carbon content of 32.60% was recorded in the organic O topsoil compared to all the other topsoils in the other soil forms (Table 6.2). Unfortunately the highest variation in data was found in the organic O topsoil (SE = 2.15). The kind and quality of organic material determines the length of storage and accumulation of organic matter in the soil (Carter, 1996). This is probably what caused a variation in the amount of organic carbon in the organic O topsoils. The organic carbon content of 24.80% in the unspecified material with signs of wetness was recorded, but it will be treated as an erroneous value because it appears excessively high.

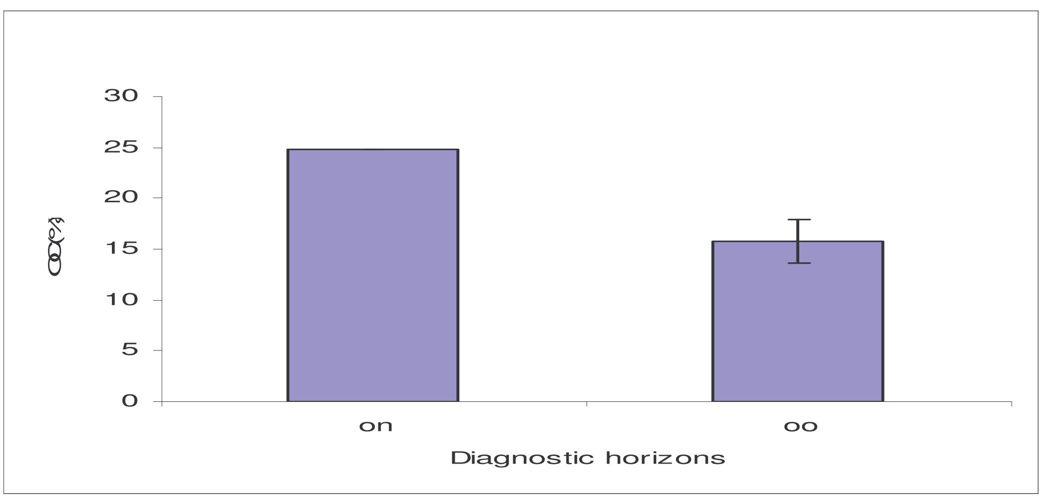


Figure 6.1 Organic carbon in soil forms with organic O topsoils: Champagne

Table 6.2 Organic carbon content of selected soil forms of South Africa

Soil form	n	Topsoil			Subsoil 1			Subsoil 2			Subsoil 3		
		Hor			Hor	n	OC (%)	Hor	n	OC (%)	Hor	n	OC (%)
Champagne (Ch)	14	oo	13	9.36-32.6 10/12.5/18.3 15.76/2.15	on	1	24.8-24.8 24.8/24.8/24.8 24.8/0						
Inanda (Ia)	71	ah	113	1-9.1 2.6/3.12/3.84 3.33/0.12	re	55	0.1-2.5 0.46/0.76/1.10 0.88/0.08	od	3	0.30-0.51 0.30/0.30/0.41 0.37/0.07			
Nomanci (No)	106	ah	98	0.60-13.28 2.43/3.26/4.39 3.89/0.24	lc	6	0.70-4.1 0.87/1.45/2.50 1.87/0.54	so	2	0.30-0.50 0.35/0.40/0.45 0.40/0.10			
Mayo (My)	199	ml	159	0.49-9.83 2.06/2.61/3.51 2.90/0.11	lc	33	0.11-2.61 0.34/0.90/1.29 0.89/0.10	so	4	0.20-0.60 0.32/0.39/0.46 0.39/0.08	ro	1	0.1-0.1 0.1/0.1/0.1 0.1/0
Bonheim (Bo)	239	ml	135	0.4-7.85 1.22/1.90/2.81 2.22/0.11	vp	80	0.1-4.44 0.40/0.6/0.99 0.81/0.08	ud	23	0.1-1.21 0.15/0.2/0.3 0.27/0.05			
Arcadia (Ar)	184	ve	161	0.1-8.4 0.8/1.29/1.92 1.57/0.09	od	23	0.1-0.8 0.4/0.4/0.4 0.4/0.05						
Rensburg (Rg)	92	ve	59	0.10-5.80 0.78/1.30/1.77 1.45/0.13	gh	31	0.10-1.36 0.20/0.30/0.50 0.37/0.05	on	2	0.30-0.40 0.33/0.35/0.38 0.35/0.05			
Avalon (Av)	576	ot	242	0.1-3.78 0.50/0.86/1.49 1.09/0.05	ye	186	0.08-7.20 0.20/0.40/0.60 0.49/0.04	sp	126	0.06-0.7 0.20/0.25/0.32 0.27/0.01	on	21	0.1-0.5 0.10/0.2/0.21 0.23/0.03
Cartref (Cf)	334	ot	202	0.2-5.15 0.77/1.17/1.7 1.34/0.06	gs	86	0.1-2.21 0.40/0.7/1.1 0.76/0.05	lc	41	0.06-1.38 0.26/0.40/0.53 0.45/0.05	so	5	0.1-0.57 0.11/0.2/0.2 0.24/0.09

Table 6.2 Continued…

Soil form	n	Topsoil			Subsoil 1			Subsoil 2			Subsoil 3		
		Hor	**n**	**OC (%)**	**Hor**	**n**	**OC (%)**	**Hor**	**n**	**OC (%)**	**Hor**	**n**	**OC (%)**
Clovelly (Cv)	976	ot	560	0.06-9.2 0.53/1.08/2.16 1.56/0.06	ye	361	0.05-4.04 0.2/0.4/0.63 0.54/0.03	so	3	0.06-0.38 0.12/0.18/0.28 0.21/0.09	od	50	0.07-2 0.1/0.2/0.39 0.35/0.06
Glenrosa (Gs)	559	ot	412	0.05-21.9 0.81/1.44/2.28 1.72/0.07	lc	128	0.1-3.4 0.3/0.5/0.8 0.64/0.05	so	15	0.1-0.64 0.2/0.20/0.39 0.27/0.04	ro	2	0.4-0.7 0.48/0.55/0.63 0.55/0.15
Hutton (Hu)	2459	ot	1290	0.03-9.6 0.47/1.02/2.05 1.41/0.03	re	1084	0.01-7.7 0.2/0.4/0.7 0.53/0.02	od	74	0.01-2.1 0.1/0.20/0.29 0.26/0.04	ro	8	0.1-0.57 0.1/0.15/0.26 0.23/0.06
Mispah (Ms)	279	ot	271	0.04-8.61 0.8/1.72/2.82 1.99/0.09	ro	7	0.10-0.80 0.10/0.40/0.55 0.37/0.11	sc	1	0.69-0.69 0.69/0.69/0.69 0.69/0			
Oakleaf (Oa)	747	ot	381	0.06-11.70 0.50/0.79/1.30 1.08/0.06	ne	317	0.02-8.1 0.20/0.37/0.60 0.51/0.03	od	43	0.03-0.60 0.10/0.15/0.24 0.19/0.02	ro	1	0.04-0.04 0.04/0.04/0.04 0.04/0
Shortlands (Sd)	425	ot	202	0.20-5.84 0.90/1.75/2.52 1.79/0.07	vr	205	0.10-4.21 0.40/0.68/1.00 0.80/0.04	od	16	0.03-1.34 0.10/0.25/0.44 0.34/0.08			
Swartland (Sw)	450	ot	224	0.1-7.15 0.64/0.92/1.55 1.28/0.07	vp	193	0.10-2.26 0.40/0.58/0.81 0.63/0.03	so	31	0.10-1.30 0.20/0.30/0.50 0.38/0.04	pr	1	0.10-0.10 0.10/0.10/0.10 0.10/0
Valsrivier (Va)	545	ot	264	0.14-5.52 0.60/0.89/1.43 1.15/0.06	vp	209	0.05-1.70 0.30/0.52/0.70 0.50/0.02	ud	64	0.04-2.22 0.10/0.20/0.30 0.27/0.04	uw	5	0.13-0.44 0.14/0.20/0.21 0.22/0.06

Hor = Diagnostic horizon: abbreviations are defined in Table 3.5
n = number of observations OC (%) is given as follows: -Range: minimum - maximum
-25th percentile/ Median/75th percentile
-Mean/Standard error

6.3.2 Soil forms with humic A topsoils

6.3.2.1 Inanda

The Inanda form is characterised by a humic A topsoil (3.33%) overlying a red apedal B (0.88%; Table 6.2), with the underlying material being unspecified dry material (0.37%; Figure 6.2). The humic A horizon in the Inanda form had a significantly lower organic carbon content than the humic A horizon in the Nomanci form (3.89%; Figure 6.6). The differences in organic carbon content in the humic A horizons in the soil forms might have been caused by the variation in the amount and type of vegetation as well as the climate prevailing in the areas where the soil forms were found (Carter, 1996). The nature of the generally hard subsoil horizon may result in slightly more pronounced wetter moisture regime in the topsoil horizon and hence slower decomposition.

The red apedal B of the Inanda form (0.88%) had a significantly higher organic carbon content than the red apedal B in the Hutton form (0.53%; Figure 6.7). The higher moisture content and lower temperatures where the humic A horizons are formed (Soil Classification Working Group, 1991; Le Roux *et al*., 1999), therefore also influenced the higher organic carbon content in the red apedal B horizons. Even though these conditions are aerobic and ideal for microbial action, the cool temperatures helped to slow down the rate of organic matter decomposition which enhances soil organic carbon conservation (Yan *et al.,* 2007).

6.3.2.2 Nomanci

The Nomanci form has a humic A topsoil (3.89%) overlying a lithocutanic B (1.87%) with saprolite (0.40%) as the underlying material (Figure 6.2). A significantly higher organic carbon content was found in the humic A topsoil of the Nomanci form (3.89%) compared to the humic A horizon in the Inanda form (3.33%; Figure 6.6). The terrain position and lower permeability of the underlying rock probably influenced the different organic carbon levels in the Nomanci and Inanda forms. The Inanda form are typically deep soils with deep weathering of underlying material. In contrast, where deep weathering of underlying material does not occur, Nomanci soils are formed. However, the areas where the Nomanci form was found probably had even lower temperatures than where the Inanda form was formed. Kirschbaum (1995) reported that as the temperature increases decomposition rate also increases. He also added that an increase of 1ºC in temperature can cause a loss of more than 10% of soil organic carbon in a soil with an average temperature of 5ºC. The amount of organic carbon in the soil also depends on the richness of organic material in nutrients

(Moges & Holden, 2008) which might be the reason why the humic A in the Inanda form had a lower organic carbon content than the humic A in the Nomanci form.

The lithocutanic B horizon (1.87%) in the Nomanci form had a significantly higher organic carbon content than in the Mayo (0.89%) or the Glenrosa (0.64%) forms (Figure 6.7). The cool and wet conditions where humic A horizons are formed, affected the organic carbon levels of the lithocutanic B horizons in the Nomanci form positively. Fey (2009) stated that the humic soils do not erode easily and have a higher potential for plant production depending on their richness in nutrients and their pH. Higher plant productivity increases the accumulation of soil organic carbon (Carter, 1996).

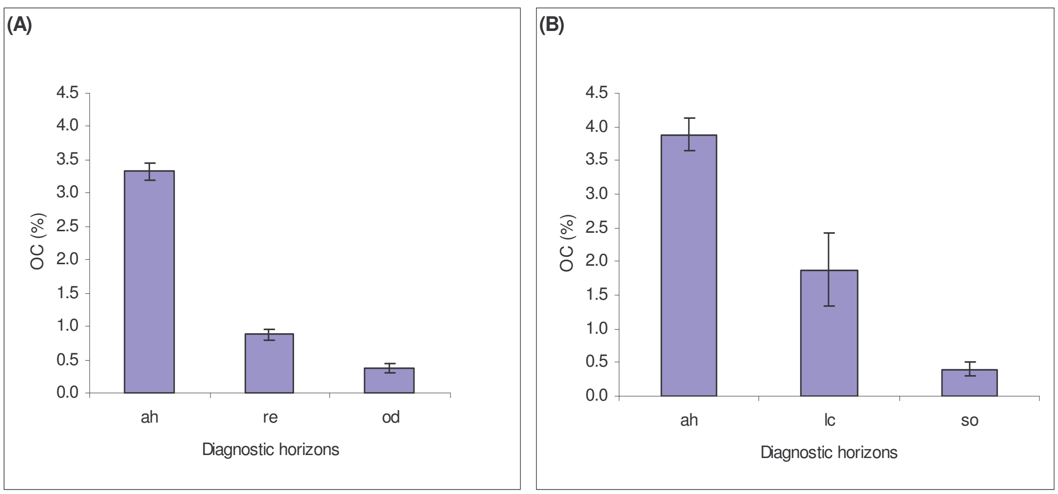


Figure 6.2 Organic carbon in soil forms with humic A topsoils: Inanda (A) and Nomanci (B)

6.3.3 Soil forms with vertic A topsoils

6.3.3.1 Arcadia

The Arcadia soil form is characterised by a vertic A topsoil, overlying unspecified dry material (Figure 6.3). The organic carbon content of the vertic A horizon (1.57%) in the Arcadia form was higher but not significantly different from the organic carbon content of the vertic A horizon in the Rensburg form (1.45%). The Arcadia and Rensburg forms have a high clay content especially in the topsoils (Le Roux *et al.,* 1999; Fey, 2009), so probably the clay in the soil forms did not differ enough to affect the organic carbon levels. The underlying unspecified dry material had the lowest organic carbon content of 0.40% in the Arcadia form.

6.3.3.2 Rensburg

The Rensburg form is characterised by a vertic A topsoil overlying a G horizon and unspecified material with signs of wetness (Figure 6.3). The organic carbon content in the vertic A (1.45%) in the Rensburg form was lower but not significantly different from the organic carbon content of the vertic A horizon in the Arcadia form (1.57%; Figure 6.6). this is to be expected since both Arcadia and Rensburg soils are commonly present in the same landscape and climate zone. They are also characterised by accumulation of organic matter in a base rich environment with swelling material.

The G horizon had an average organic carbon content of 0.37%, ranging from 0.10% to 1.36%. The G horizon of the Rensburg and the unspecified material with signs of wetness in the Champagne form are both gley soils, but the organic carbon content in the former horizon could not be compared because of their significantly different nature of their genesis, Apparently the erroneous value of 24.80% of organic carbon was recorded in the latter horizon. Surprisingly, the organic carbon content in the G horizon in the Rensburg was significantly lower than the organic carbon content of the E horizon in the Cartref form (0.76%). This was not expected because according to the Soil Classification Working Group (1991) there has to be removal of colloidal matter, including organic matter and clay from the E horizon and not in the G horizon. Since clay and organic carbon have a close positive relationship by strengthening and shielding soil organic matter against decomposition (Torn *et al*., 1997), the organic carbon content in the G horizon in the Rensburg form was expected to be higher than in the E horizon in the Cartref form. The higher clay content in the vertic A horizon in the Rensburg form and the illuviation of clay particles did not influence the higher organic matter levels in the G horizon. Clay probably did not affect the organic carbon levels in the G horizon because the relationship between soil organic carbon and texture relies heavily on the parent material (Kadeba, 1977).

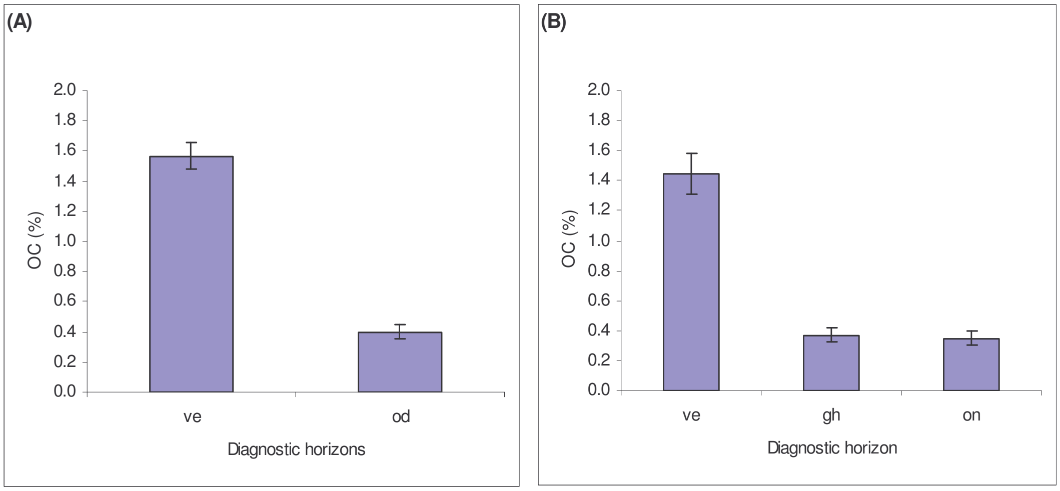


Figure 6.3 Organic carbon in soil forms with vertic A topsoils: Arcadia (A) and Rensburg (B)

6.3.4 Soil forms with melanic A topsoils

6.3.4.1 Mayo

The Mayo soil form is characterised by a melanic A topsoil overlying a lithocutanic B horizon and a saprolite or hard rock as the underlying material (Figure 6.4). The organic carbon content in the melanic A (2.90%) of the Mayo form was significantly higher than in the melanic A in the Bonheim form (2.22%). Van der Merwe *et al.* (2002) stated that climate is the main soil forming factor in the formation of melanic soils. Therefore the differences in organic carbon content in the melanic A horizons in the Mayo and Bonheim forms may be a result of variation in *e.g.* rainfall and temperature in areas where they were formed.

The lithocutanic B horizon (0.89%) in the Mayo form had significantly higher organic carbon content than the lithocutanic B horizon in the Glenrosa form (0.64%), but was significantly lower than the lithocutanic B horizon in the Nomanci form (1.87%; Figure 6.7). The difference may have been a result of different soil temperature, precipitation, vegetation and topographical position (Carter, 1996; Jones *et al.,* 2004a). The organic carbon content in the lithocutanic B horizons in the respective soil forms seemed to be directly proportional to the organic carbon of the overlying topsoils. According to Table 6.2, the organic carbon content of the topsoils in the Nomanci, Mayo, and Glenrosa forms decreased as follows: humic A (3.89%) > melanic A (2.90%) > orthic A (1.72%) respectively. Similarly the organic carbon content in the lithocutanic B horizons in the three soil forms decreased from the Nomanci (1.87%) > Mayo (0.89%) > Glenrosa (0.64%).

6.3.4.2 Bonheim

The Bonheim form has a melanic A topsoil overlying a pedocutanic B (Figure 6.4) and unconsolidated material without signs of wetness. The organic carbon content in the melanic A in the Bonheim form (2.22%) was significantly lower than the organic carbon content in the melanic A horizon in the Mayo form (2.90%; Figure 6.6). The melanic topsoils are formed in semi-arid to humid/sub-humid conditions (Le Roux *et al.,* 1999; Van der Merwe *et al.,* 2002).

The pedocutanic B horizon in the Bonheim soil form had a significantly higher organic carbon content (0.81%) compared to the pedocutanic B horizons in the Swartland (0.63%) and Valsrivier (0.50%) forms (Figure 6.7). The conditions that have lead to a higher organic carbon content in the melanic topsoil probably also influenced higher organic carbon levels in the subsoil.

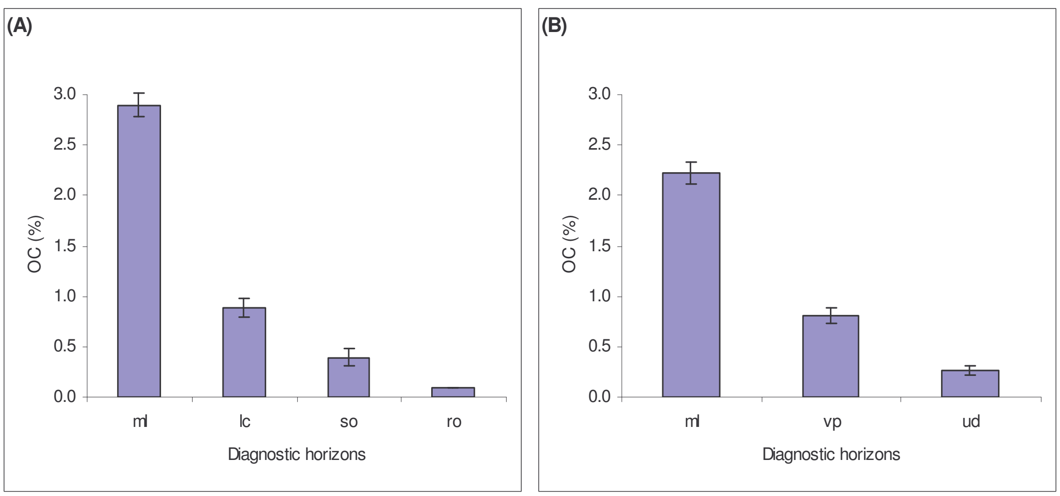


Figure 6.4 Organic carbon in soil forms with melanic A topsoils: Mayo (A) and Bonheim (B)

6.3.5 Soil forms with orthic A topsoils

6.3.5.1 Clovelly

The Clovelly soil form is characterised by the orthic A topsoil and the yellow-brown apedal B with unspecified dry material or saprolite as the underlying materials (Figure 6.5; Table 6.2). Organic carbon in this soil form ranged from 1.56% in the orthic A to 0.21% in the saprolite. The organic carbon content in the orthic A in the Clovelly form (1.56%) was significantly higher than the organic carbon in the orthic A in the Oakleaf (1.08%), Avalon (1.09%), Valsrivier (1.15%), Swartland (1.28%), Cartref (1.34%), and Hutton (1.41%) forms (Figure 6.4). On the other hand, the organic carbon content in the orthic A of the Clovelly form was significantly lower than in the orthic A horizons of the Glenrosa (1.72%), Shortlands (1.79%), and Mispah (1.99%) forms. According to the soil groups of Fey (2009), the Clovelly, Hutton, and Shortlands form are oxidic soils. The orthic A in the Clovelly form was expected to have a higher organic carbon content than in the Hutton form because of the higher soil water regimes based on the underlying diagnostic horizons.

A wetter soil water regime is required for the formation of the yellow-brown apedal B (Clovelly) than the red apedal B (Hutton) horizons (Soil Classification Working Group, 1991). This water content probably had a positive effect on the organic carbon content of the orthic A in the Clovelly form. On the other hand, the organic carbon content of the yellow-brown apedal B horizon in the Clovelly (0.54%) was not significantly different from the organic carbon content of the yellow-brown apedal B in the Avalon form (0.49%; Figure 6.7). There was also no significant difference in organic carbon content between the yellow-brown apedal B horizon in the Clovelly, red apedal B (0.53%) in the Hutton, and the neocutanic B (0.51%) in the Oakleaf forms.

6.3.5.2 Glenrosa

The Glenrosa soil form has an orthic A topsoil overlying a lithocutanic B horizon (Figure 6.5). The underlying materials are saprolite and hard rock. The organic carbon content of the orthic A (1.72%) in the Glenrosa form had a significantly higher organic carbon content than the orthic A horizons in the Oakleaf (1.08%), Avalon (1.09%), Valsrivier (1.15%), Swartland (1.28%), Cartref (1.34%), Hutton (1.41%), and Clovelly (1.56%) forms (Figure 6.6). There was probably less permeability for water and plant roots in the underlying lithocutanic B horizon in the Glenrosa form since the hardness of the lithocutanic B horizon varies depending on the degree of weathering and structure of the rock from which it was made (Le Roux *et al*., 1999). Perhaps this resulted in more water content in the orthic A which probably improved plant growth and lead to more production of organic material hence more organic carbon content in the orthic A in the Glenrosa form. However, the organic carbon content in the orthic A in the Glenrosa form was significantly lower than in the Mispah form but was not significantly different from the Shortlands form. According to Fey (2009), the Glenrosa and Mispah forms are both inceptic soils of the lithic subgroup. Therefore, the differences in organic carbon content in the orthic A horizons of the Glenrosa and Mispah forms, was probably caused by differences in the amount of organic material as well as environmental conditions where they were found.

The lithocutanic B horizon in the Glenrosa form (0.64%) had a significantly lower organic carbon content than the lithocutanic B horizons in the Mayo (0.89%) and Nomanci (1.87%) forms (Figure 6.7). The wet and cool soil forming factors governing the formation of the overlying topsoil of the humic A horizons, probably also resulted in the higher organic carbon content of the underlying lithocutanic B horizon.

6.3.5.3 Hutton

The Hutton soil form is the most dominant soil form sampled in South Africa, with 1290 observations (Table 6.2). The organic carbon content of the orthic A (1.41%) in the Hutton form was significantly higher than in the orthic A in the Oakleaf (1.80%), Avalon (1.09%), Valsrivier (1.15%), and Swartland (1.28%) forms (Figure 6.6). The orthic A horizons in the Clovelly (1.56%), Glenrosa (1.72%), Shortlands (1.79%) and Mispah (1.99%) forms had a significantly higher organic carbon content than the orthic A in the Hutton form. This may be a result of differences in climate, vegetation type, and position in the landscape (Carter, 1996). A combination of wetter soil conditions and vegetative material rich in organic carbon found in the lower parts of the landscape or concave slopes may have probably lead to more organic carbon in the Clovelly, Glenrosa, Shortlands, and Mispah forms. There was no significant difference in the organic carbon content of the orthic A in the Hutton and Cartref forms. According to Fey (2009), the Hutton form is a typical example of an oxidic soil and the Cartref of a hydromorphic soil. More organic carbon was therefore expected in the Cartref form than in the Hutton form.

The red apedal B in the Hutton form (0.53%) had a significantly lower organic carbon content than the red apedal B horizon in the Inanda form (0.88%; Figure 6.7). The higher water conditions associated with the formation of the Inanda form probably promoted the significantly higher organic carbon content in the red apedal B horizon of the Inanda form (Fey, 2009).

6.3.5.4 Mispah

The Mispah soil form has an orthic A topsoil overlying hard rock (Figure 6.5). The organic carbon content in the orthic A horizon (1.99%) in this form was significantly higher than in all the other soil forms: Oakleaf (1.08%), Avalon (1.09%), Valsrivier (1.15%), Swartland (1.28%), Cartref (1.34%), Hutton (1.41%), Clovelly (1.56%), Glenrosa (1.72%), and Shortlands (1.79%; Figure 6.6).

The lithocutanic B horizon of the Glenrosa form and the hard rock of the Mispah form are diagnostic horizons for the lithic subgroup of the inceptic soils (Fey, 2009). The organic carbon content of the Glenrosa lithocutanic B horizon (0.64%) was significantly higher than the hardrock (0.37%) of the Mispah form. This is probably because there is very limited access of soil, water and plant roots in the hard rock layer (Le Roux *et al.*, 1999).

6.3.5.5 Oakleaf

The Oakleaf soil form is characterised by the orthic A topsoil, the neocutanic B horizon as the subsoil, and unspecified dry material and hard rock as the underlying materials (Figure 6.5). The organic carbon content of 1.08% in the orthic A of the Glenrosa form was not significantly different from the organic carbon content of the orthic A horizons in the Avalon (1.09%) and Valsrivier (1.15%) forms (Figure 6.6). The orthic A horizons in the Swartland (1.28%), Cartref (1.34%), Hutton (1.41%), Clovelly (1.56%), Glenrosa (1.72%), Shortlands (1.79%), and Mispah (1.99%) forms had significantly higher organic carbon content than the Oakleaf form. The neocutanic B in the Oakleaf form had an organic carbon content of 0.51%.

6.3.5.6 Shortlands

The Shortlands form is made up of the orthic A topsoil overlying the red structured B horizon with unspecified dry material as the underlying material (Figure 6.5). The orthic A topsoil in the Shortlands form (1.79%) had significantly higher organic carbon than the orthic A horizons in the Oakleaf (1.08%), Avalon (1.09%), Valsrivier (1.15%), Swartland (1.28%), Cartref (1.34%), Hutton (1.41%), and Clovelly (1.56%) forms (Figure 6.6). There was no significant difference in the organic carbon content of the orthic A horizons in the Shortlands and Glenrosa form. The orthic A in the Mispah form (1.99%) had a significantly higher organic carbon content than the Shortlands form.

Fey (2009) stated that the Shortlands, Hutton, and Clovelly forms are oxidic soils. However, the red structured B in the Shortlands soil had a significantly higher organic carbon content (0.80%) than the red apedal B (0.53%) in the Hutton and the yellow-brown apedal B (0.54%) in the Clovelly, probably because of the higher clay content. Fey (2009) stated that the red structured B horizons of the Shortlands form have more clay than the yellow-brown apedal and red apedal B horizons. Clay content has been proven to have a positive influence on the organic carbon content of the soil (Spain, 1990; Jobbagy & Jackson, 2000).

6.3.5.7 Swartland

The Swartland soil form is characterised by the orthic A overlying the pedocutanic B over saprolite (Figure 6.5). The organic carbon content in the orthic A in the Swartland form (1.28%) was significantly higher than in the orthic A horizons in the Oakleaf (1.08%) and Avalon (1.09%) forms (Figure 6.6). The organic carbon content of the orthic A horizons in the Hutton (1.41%), Clovelly (1.56%), Glenrosa (1.72%), Shortlands (1.79%), and Mispah (1.99%) was significantly higher than in the Swartland form. There was no significant difference in organic carbon content between the orthic A horizons in the Swartland, Cartref (1.34%), and Valsrivier (1.15%) forms. The organic carbon content in the pedocutanic B horizons in the Bonheim form (0.81%) was significantly higher than in the Swartland (0.63%) which was significantly higher than in the Valsrivier form (0.50%; Figure 6.7).

6.3.5.8 Valsrivier

An orthic A overlying a pedocutanic B and unconsolidated material without signs of wetness are characteristic of the Valsrivier soil form (Figure 6.5). The organic carbon of the orthic A horizon in the Valsrivier form (1.15%) was not significantly different from the organic carbon content in the Oakleaf (1.08%) and Avalon (1.09%) but was significantly lower than in the Cartref (1.34%), Hutton (1.41%), Clovelly (1.56%), Glenrosa (1.72%), Shortlands (1.79%), and Mispah (1.99%) forms (Figure 6.6). There was no significant difference in the organic carbon content of the orthic A horizons in the Valsrivier and Swartland (1.28%) forms. This is probably because they are both duplex soils and are therefore formed under similar climatic conditions that allow the illuviation of clay (Soil Classification Working Group, 1991; Fey 2009).

The pedocutanic B horizon in the Valsrivier form had a significantly lower organic carbon content of 0.50% when compared to 0.63% of the pedocutanic B horizon in the Swartland form (Figure 6.7). Since the Valsrivier and Swartland forms are both duplex forms, the difference in organic carbon content in the pedocutanic B horizons may have been caused by climate and topographical position of the soils, land use practices as well as the type of vegetation (Carter, 1996). However, the pedocutanic B horizon in the Valsrivier form had a significantly lower organic carbon content than the pedocutanic B horizon in the Bonheim form (0.81%).

6.3.5.9 Avalon

The Avalon soil form is characterised by an orthic A topsoil overlying a yellow-brown apedal B and a soft plinthic B horizon (Figure 6.5). The organic carbon content in the orthic A (1.09%) in the Avalon form was not significantly different from the organic carbon content in the orthic A horizons in the Oakleaf (1.08%) and Valsrivier (1.15%) forms (Figure 6.6). The amount of organic carbon in the orthic A in the Avalon form was significantly lower than in the orthic A horizons in the Swartland (1.28%), Cartref (1.34%), Hutton (1.41%), Clovelly (1.56%), Glenrosa (1.72%), Shortlands (1.79%), and Mispah (1.99%) forms. The periodic wetness associated with the formation of the diagnostic horizons of the Avalon form therefore did not influence the organic carbon levels of the orthic A horizon in the Avalon form.

The yellow-brown apedal B horizon in the Avalon form (0.49%) had lower organic carbon content than the yellow-brown apedal B in the Clovelly form (0.54%) but the difference was not significant. The opposite was expected, due to a higher water content associated with the presence a fluctuating water table in the Avalon form when compared to the Clovelly form. A probable explanation might be that the water content in the Avalon form was enough to increase the rate of mineralisation instead of providing anaerobic conditions that would slow down microbial action (Havlin *et al.,* 1999).

6.3.5.10 Cartref

The Cartref form is described as an orthic A and E horizon overlying a lithocutanic B horizon (Figure 6.5). The underlying material is saprolite. The highest organic carbon content was found in the orthic A at 1.34% (Table 6.2). The organic carbon content in the orthic A of the Cartref form was significantly higher than in the Oakleaf (1.08%), Avalon (1.09%), and Valsrivier (1.15%) forms (Figure 6.6). According to Fey (2009), the Cartref form is a hydromorphic soil and has a tendency to be wet. This high water content probably helped reduce the rate of soil organic matter mineralisation or probably promoted more plant productivity therefore increasing organic material in the orthic A topsoil (Carter, 1996; Havlin *et al*., 1999). The amount of organic carbon in the orthic A in the Cartref form was significantly lower than in the orthic A horizons in the Clovelly (1.56%), Glenrosa (1.72%), Shortlands (1.79%), and Mispah (1.99%) forms. The organic carbon content in orthic A horizon in the Cartref form was not significantly different from the organic carbon content in the orthic A horizons in the Swartland (1.28%) and Hutton (1.41%) forms. The E horizons (0.76%) of the Cartref form had a significantly higher organic carbon content than the G horizons (0.37%) of the Rensburg form. The removal of colloidal material, including organic matter (Soil Classification Working Group, 1991), did not significantly affect the organic carbon levels of the E horizon.

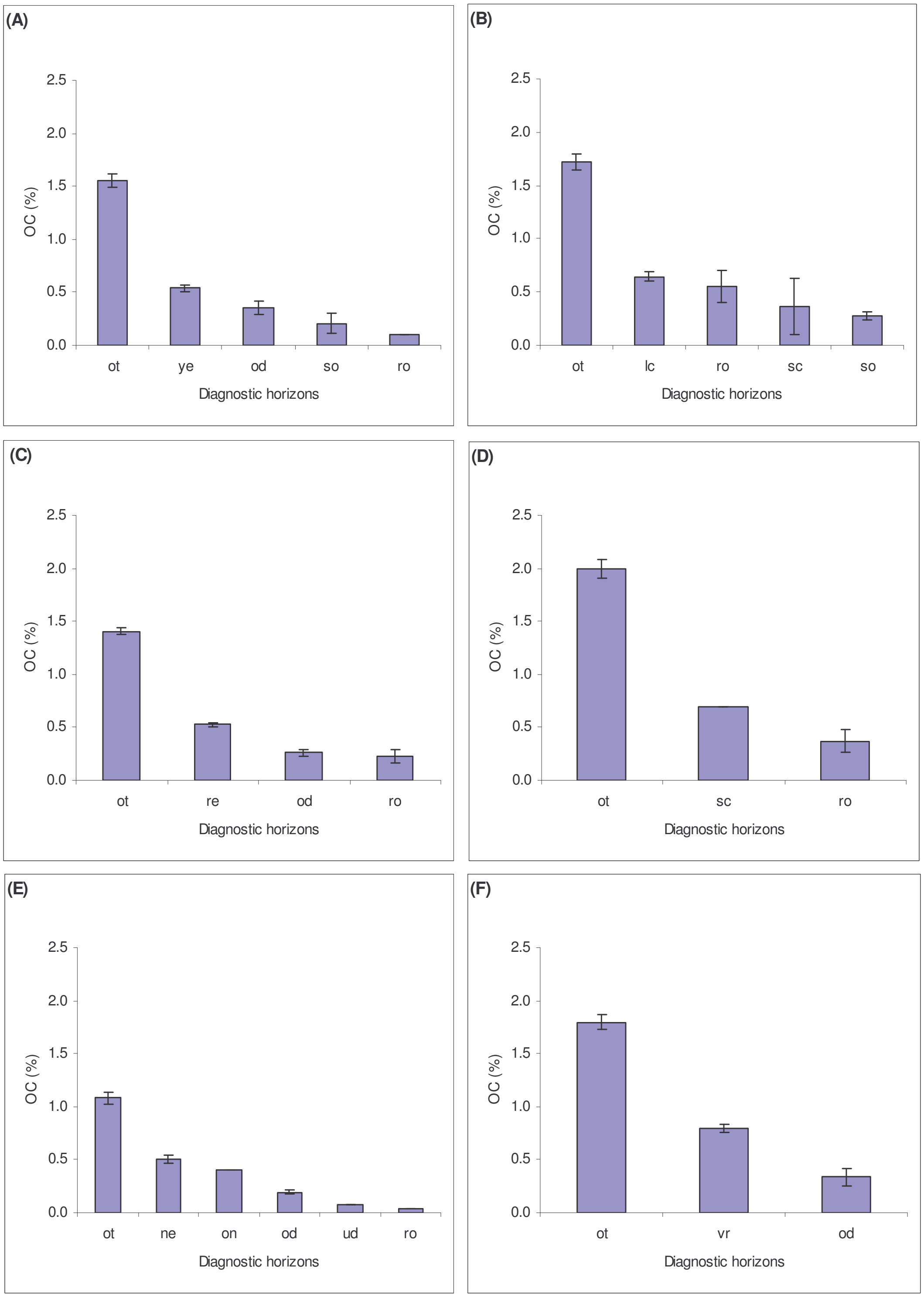


Figure 6.5 Organic carbon in soil forms with orthic A topsoils: Clovelly (A), Glenrosa (B), Hutton (C), Mispah (D), Oakleaf (E), Shortlands (F), Swartland (G), Valsrivier (H), Avalon (I), and Cartref (J)

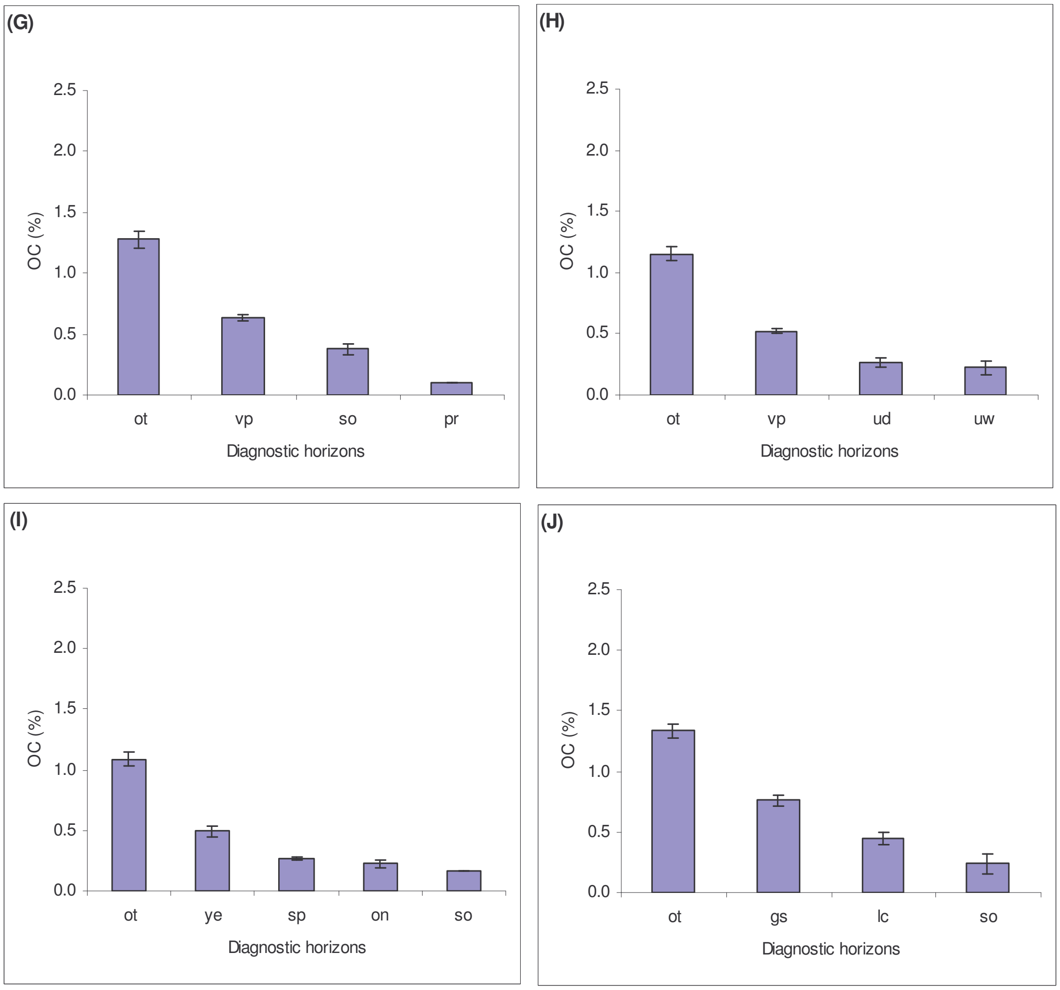


Figure 6.5 Continued …

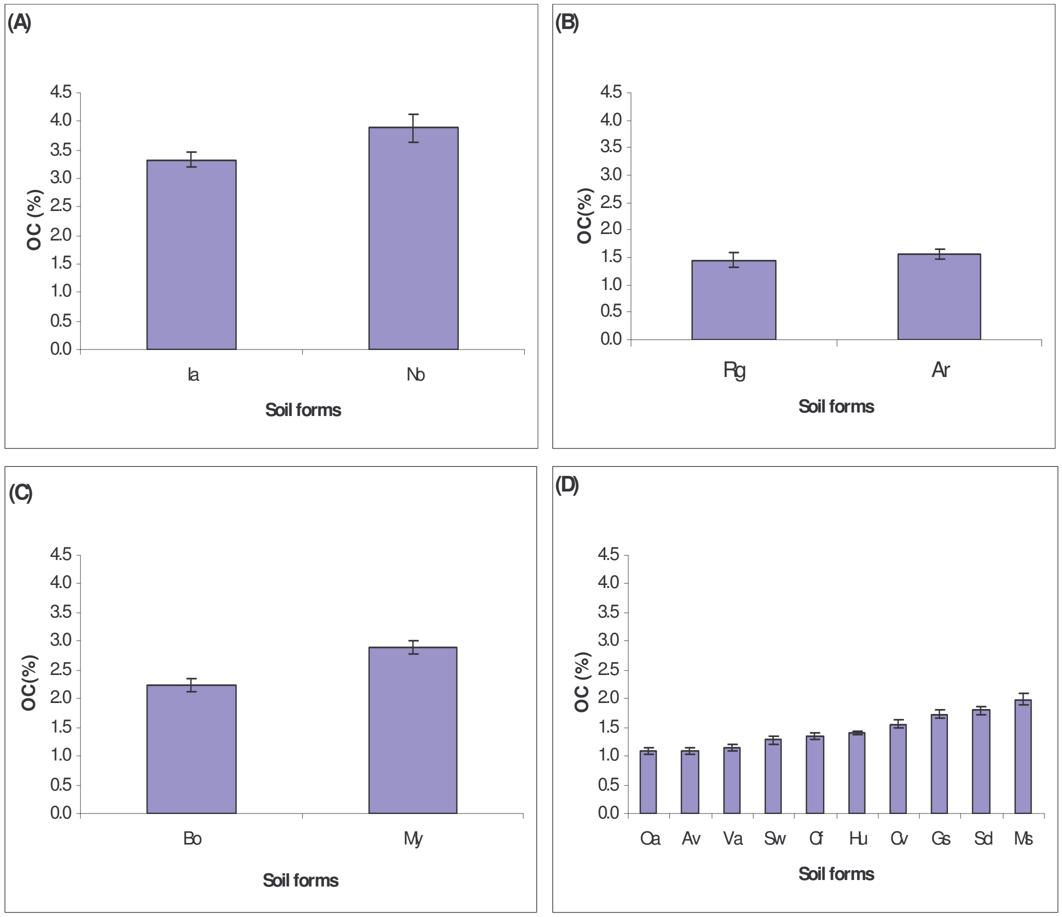


Figure 6.6 Organic carbon in soil forms with humic A horizons (A): Inanda (Ia) and Nomanci (No) forms, vertic A horizons (B): Rensburg (Rg) and Arcadia (Ar) forms, melanic A horizons (C): Bonheim (Bo) and Mayo (My) forms, and orthic A horizons (D): Oakleaf (Oa), Avalon (Av), Valsrivier (Va), Swartland (Sw), Cartref (Cf), Hutton (Hu), Clovelly (Cv), Glenrosa (Gs), Shortlands (Sd), and Mispah (s) forms,

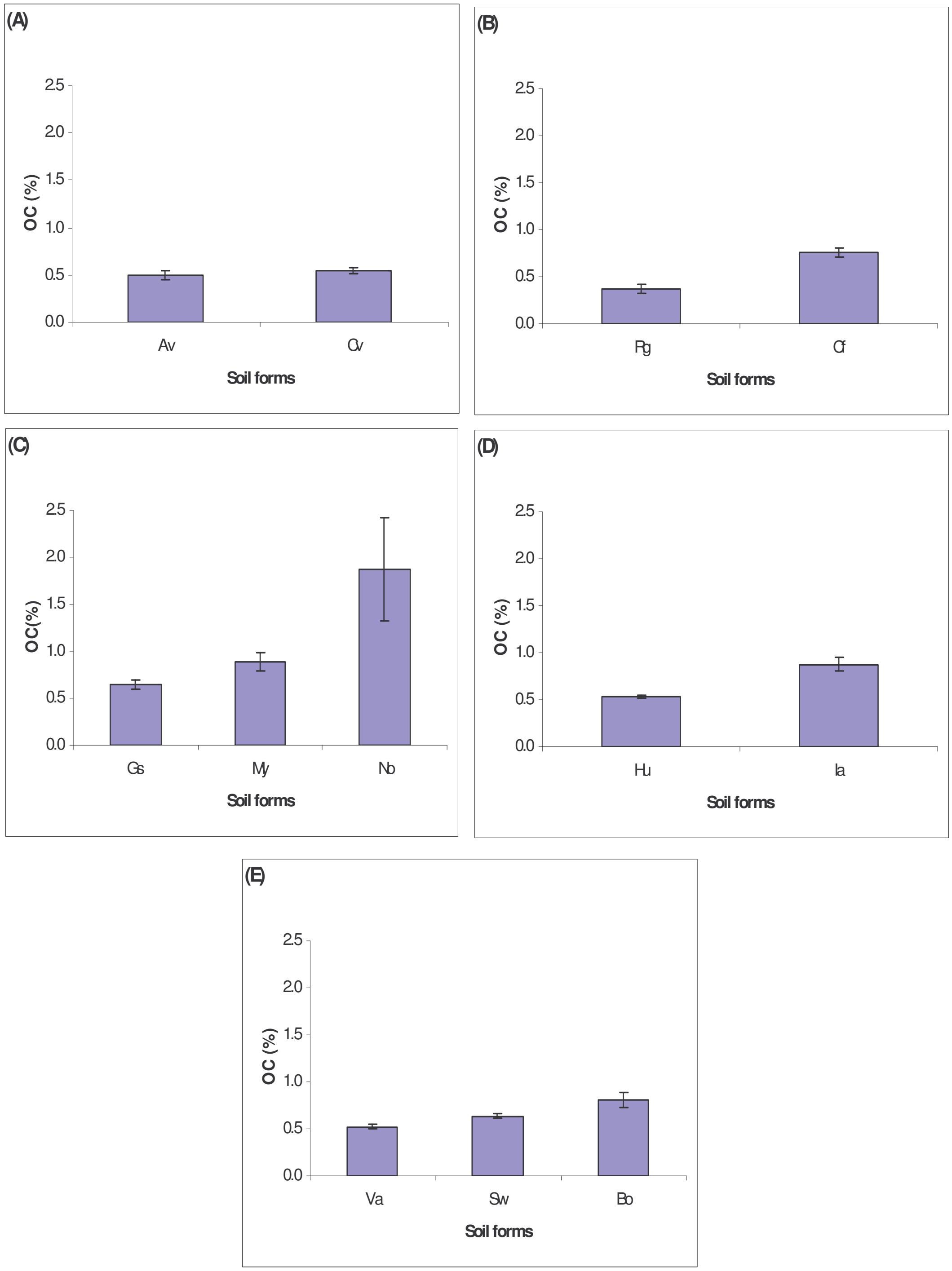


Figure 6.7 Organic carbon content in the yellow-brown apedal B horizons (A): Avalon (Av) and Clovelly (Cv), gley soils (B): Rensburg (Rs) and Cartref (Cf) forms, lithocutanic B horizons (C): Glenrosa (Gs), Mayo (My), and Nomanci (No) forms, red apedal B horizons (D): Hutton (Hu) and Inanda (Ia) forms, pedocutanic B horizons (E): Valsrivier (Va), Swartland (Sw), and Bonheim (Bo) forms

6.4 Conclusions

The average organic carbon content in the soil forms of South Africa varies depending on the diagnostic horizons that describe them. The amount of organic carbon in these soils followed the same pattern that was revealed by the topsoils in Chapter 5. The organic carbon content of the diagnostic topsoils followed this pattern organic O > humic A > melanic A > vertic A > orthic A. The diagnostic horizons underlying the topsoils with highest amount of organic carbon content still had significantly higher organic carbon than their counterparts in other soil forms. For example, the lithocutanic B horizon underlying the melanic A horizon in the Mayo form had significantly higher organic carbon content than the lithocutanic B horizon underlying the orthic A in the Glenrosa form, whereas the lithocutanic B horizon underlying the humic A in the Nomanci form had a significantly higher organic carbon than the lithocutanic B in the Mayo form. The environmental conditions that influenced the organic carbon content of the topsoils therefore also influenced the organic carbon content in the diagnostic subsoil horizons of that particular soil form.

The differences in climate, vegetation type, and topographical positions of the soil forms resulted in the same diagnostic horizons having different organic carbon contents depending on the soil form in which it was found. For example, the lithocutanic B horizon in the Nomanci form had significantly higher organic carbon content than the lithocutanic B horizons in the Glenrosa and Mayo forms. Since the Nomanci form is formed in cool moist areas, the conditions promoted higher organic carbon content in all the diagnostic horizons in this form compared to when they are in other forms.

CHAPTER 7
ORGANIC CARBON STOCKS IN THE SOILS OF SOUTH AFRICA

7.1 Introduction

There are two groups of factors that influence soil organic carbon content: natural factors (climate, parent material, land cover and/or vegetation, and topography) and human induced factors (land use, management, and degradation). The interdependence of these factors on each other as well as their variation has largely contributed to the varying amount of organic carbon in soils (Jones *et al.,* 2004a). Regardless of the climate of an area, the texture of a soil also can influence the amount of organic carbon in it (Alvarez & Lavado, 1998).

Therefore, the amount of organic matter in soil varies widely, from at least one to ten percent (Gregorich *et al*., 2007). However, most South African soils contain less than 2% organic matter. De Villiers *et al.* (2002) agree that almost 60% of the soils in South Africa have a low soil organic matter content, resulting in low soil productivity and soil degradation. Scotney and Dijkhuis (1990) add that the virgin soils of South African have very low soil organic matter levels. This may be related to the use and management of the soils, which actually influences the accumulation or loss of organic matter in soils. Therefore the status of organic matter and its indices C and N should be correctly quantified, followed by relevant conservation measures to restore the organic matter resources.

Even though there have been studies on the organic matter levels in South African soils, little has been done to investigate thoroughly how soil organic carbon is affected by various situations (Barnard, 2000). Barnard (2000) studied the status of organic matter in South African virgin soils. He found that the organic carbon content of the soils ranged from less than 0.5% to more than 4%. Only 4% of the soils contained more than 2% organic carbon and 58% of the soils contained less than 0.5% organic carbon. The remaining 38% of the soils contained 0.5 to 2% organic carbon (Du Preez, 2000).

Cultivation of virgin soils was identified as one of the primary causes of declining soil organic carbon levels in South Africa (Van Zyl & Du Preez, 1997). Other activities that resulted in a decline in the organic carbon status of soil include: land use practices such as cropping under dry land and irrigation, stock farming, and forestry (Arrouays *et al.,* 2001). For example, Du Preez & Snyman (1993) reported lower organic carbon levels under areas with poor basal cover than in areas with a good vegetation cover. In addition to those human activities there are natural conditions that resulted in lower organic carbon levels in the soils. Those natural conditions include: climate, parent material, land cover and/or vegetation, and topography (Jones *et al.,* 2004a).

However, in order to evaluate the impact of the natural and human activities on soil organic carbon contents, an accurate amount of soil organic carbon stocks has to be known. With the increasing alarm of the addition of C to the atmosphere as carbon dioxide, baseline data on organic carbon stocks is very important and will help in determining whether the soils of South Africa are still fertile or not and whether they have a potential for C sequestration.

Burke *et al.* (1989) stated that the organic carbon content of soil depends upon the interaction between topography, climate, and texture as well as land use practices. As mentioned in the literature study several scientists have successfully calculated the amount of organic carbon in the soils of their respective countries. Brejda *et al.* (2001) and Meersmans *et al.* (2008) estimated the organic carbon stocks by considering the amount of moisture in the soil, land use practices, topography, and soil texture.

According to Benites *et al*. (2007), the success of calculating soil organic carbon stocks depends on the accessibility of soil bulk density data (D_b) and soil organic carbon data (preferably in g C kg^{-1} soil). Some databases do not have soil bulk density data but fortunately it has been successfully estimated by several scientists around the world using measured soil properties (Manrique *et al.,* 1991; Benites *et al.,* 2007). Rawls (1983) also developed a method that could be used for predicting soil bulk density using particle size and organic matter data. Therefore, prior to implementing mitigation strategies that will help conserve soil organic carbon and reduce the increasing C in the atmosphere, estimation of the current organic carbon stocks of South African soils should be done as a benchmark.

7.2 Procedure

The land type data was used to estimate the amount of organic carbon in the soils of South Africa (Land Type Survey Staff, 2003). This data was collected during a land type survey that started in 1970. Each land type displays a certain level of uniformity in terms of terrain morphology, climate and soil pattern. A number of soil profiles, called modal profiles were chosen to signify the range of soils encountered in the survey. The Binomial Soil Classification System for South Africa (MacVicar *et al.,* 1977) was used for the land type survey whilst the Taxonomic Soil Classification System for South Africa (Soil Classification Working Group, 1991) was utilized for the later surveys. Approximately 2 200 modal profiles representing 6 461 samples all over South Africa were sampled and analyzed for physical and chemical properties. The sand, silt, and clay percentages were included as well as the amount of soil organic carbon. The particle size distribution was determined as described by Day (1965) and the soil organic carbon content was determined using the Walkley-Black method as described by Allison (1965). Only the data points with organic carbon content of more than zero were used and those with missing organic carbon data were deleted from the database.

All the numeric variables that play a vital role in soil formation that were available in the database were used to develop models for estimating organic carbon in master (Chapter 4) and diagnostic (Chapter 5) horizons. Unfortunately, the outcomes of the models were not convincing for them to be used to estimate the levels of organic carbon in South African soils. Therefore, the equation by Howard *et al*. (1995) as shown below was used to estimate the level of organic carbon stocks in South African soils.

$$C_t = D_b \times \%C \times D \times A \qquad (7.1)$$

Where: C_t = Soil organic carbon stock (kg ha^{-1})

D_b = Soil bulk density (g cm^{-3})

%C = Soil organic carbon concentration (%)

D = Sampling depth (cm)

A = Sampling area (taken as 1 ha)

This equation as most others (Chapter 2) that can be used to estimate soil organic carbon stocks require soil bulk density as input. Unfortunately, the land type survey data does not include soil bulk density measurements. Therefore a model had to be computed to estimate soil bulk density. A prerequisite for such a model is that the independent variables included must be available in the database of the land type survey.

Based on research done by Benites *et al*. (2007) an appropriate model for South Africa was developed using data from published research: Hensley (1984), Haarhoff (1989), Hattingh (1993), Musto (1994), Van Huyssteen (1995), Hensley *et al.* (1996), Hensley *et al.* (1997), and Hensley *et al.* (2000). This data was chosen in such a way that it represented the different soils found all around South Africa to reduce bias. The multiple regression as shown in Equation 7.2 resulted in a good correlation coefficient (R^2 = 0.74). This equation was used to calculate bulk density values to compare with an independent set of measured bulk density values in testing its accuracy (Figure 7.1).

$$Y = 1.792 - 0.140(C) - 0.006(Clay) - 0.002(Sand) - 0.001(Silt) + 0.006(S_{value}) \quad (7.2)$$

Where: Y = Soil bulk density (g cm^{-3})

C = organic carbon content (%)

Clay = Clay content (%)

Sand = Sand fraction (%)

Silt = Silt fraction (%)

S_{value} = Sum of basic cations (cmolc kg^{-1} soil)

The accuracy of Equation 7.2 is of such a nature that soil bulk density can be estimated if all the independent variables are known as for all the profiles sampled in the land type survey. Unfortunately, for the areas which were not sampled the independent variables will have to be estimated before an attempt of estimating soil bulk density and ultimately soil organic carbon stock. This will introduce more error into interpolated soil organic carbon stock data.

Figure 7.2 shows a histogram that was made to see the distribution of the data that was used to test the bulk density model. This diagram shows that most South African soils have bulk densities falling between 1.30 g cm^{-3} and 1.70 g cm^{-3}. It was decided therefore to estimate organic carbon stocks of South African soils using three bulk densities: minimum = 1.30 g cm^{-3}, average = 1.50 g cm^{-3}, and maximum = 1.70 g cm^{-3}. The minimum, average, and maximum organic carbon stocks of 6 461 soil samples (Figure 7.3) were estimated with Equation 7.1. For this exercise the organic carbon contents of their master A horizons were used, assuming that they are all at least 300 mm thick.

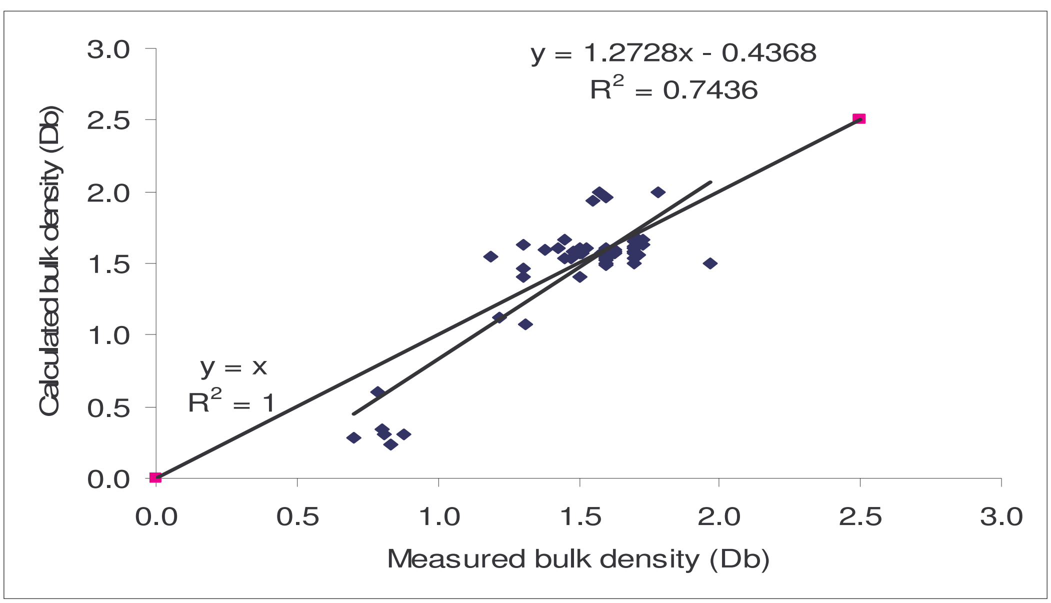


Figure 7.1 Relationship between calculated and measured soil bulk densities

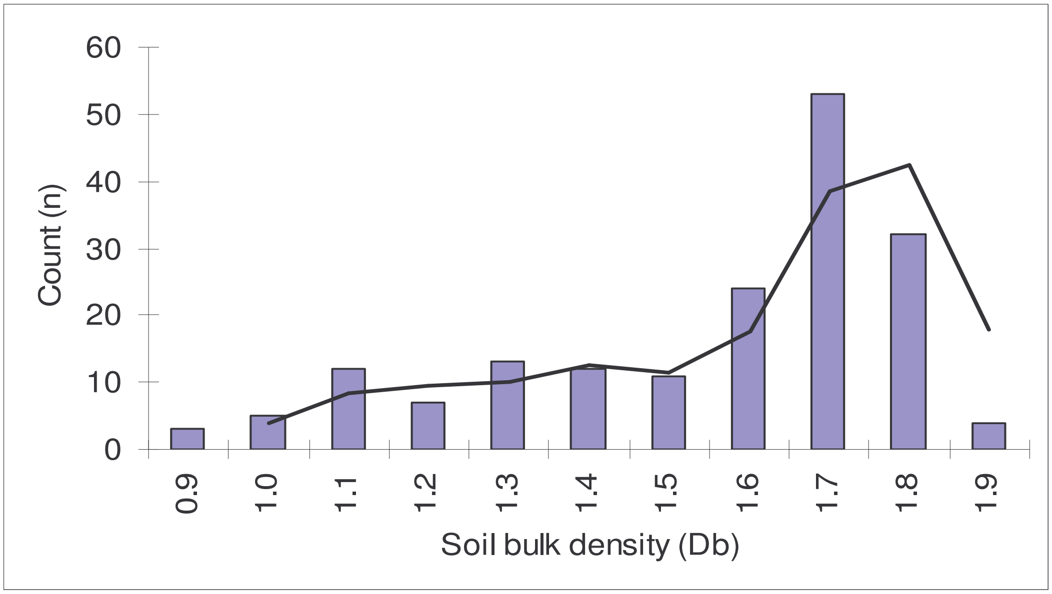


Figure 7.2 Distribution of soil bulk density data used to test the model

After the calculation of the organic carbon stocks for the modal profiles, the values were then interpolated in the Geostatistical Wizard Analyst tools using the inverse distance weighting method (IDW) to obtain a carbon stock map for South Africa. The nearest neighbours were used at a power of 2. This method is a multivariate interpolation where unknown points are fitted in with values by using known values from other known scattered points. These new values are weighted by distance from the interpolation location. A lower power of 2 was used to give more weight to the points that are farther away and this resulted in a smoother surface (Environmental Systems Research Institute, 2005). A relationship between soil organic carbon stocks and rainfall was investigated. Rainfall data was taken from Schulze (2006).

7.3 Results and discussion

The average organic carbon stocks of 6 461 soil samples in South African were 63 896, 73 726, and 83 556 kg ha^{-1} when bulk densities of respectively 1.30 1.50, and 1.70 g cm^{-3} were used in the estimations (Table 7.1). Based on a soil bulk density of 1.50 g cm^{-3}, the 25th percentile, median, and 75th percentile organic carbon stocks were estimated as 27 540, 54 000, and 102 150 kg ha^{-1}, respectively.

Table 7.1 Some statistical data on soil organic carbon stocks of modal profiles in South Africa

Bulk density (g cm^{-3})	Soil organic carbon stocks (kg ha^{-1})					
	Range	Mean	Standard error	25th percentile	Median	75th percentile
1.30	390 - 854 100	63 896	722	23 790	46 800	88 530
1.50	450 - 985 500	73 726	833	27 450	54 000	102 150
1.70	510 - 1 116 900	83 556	944	31 110	61 200	115 770

According to the Soil Survey Staff (1975), the soils of the world have a total organic carbon content of 1576 Pg (1 Pg = 10^{15} g) calculated to a depth of 1 m stored in them. However, based on a bulk density of 1.50 g cm^{-3} the organic carbon stock of South African soils to a depth of 0.30 m is estimated to be 8.99 ± 0.10 Pg. This means that on average the soils of South Africa contain 0.57% of the world's soil organic carbon with South Africa covering about 0.82% of the world's total land area. Unfortunately this value cannot be used as a representative value for the carbon stocks of South Africa in relation to the worlds because organic carbon is expected to decrease with depth. Therefore a lower value will be expected if carbon stocks are estimated to a depth of 1 m in South Africa.

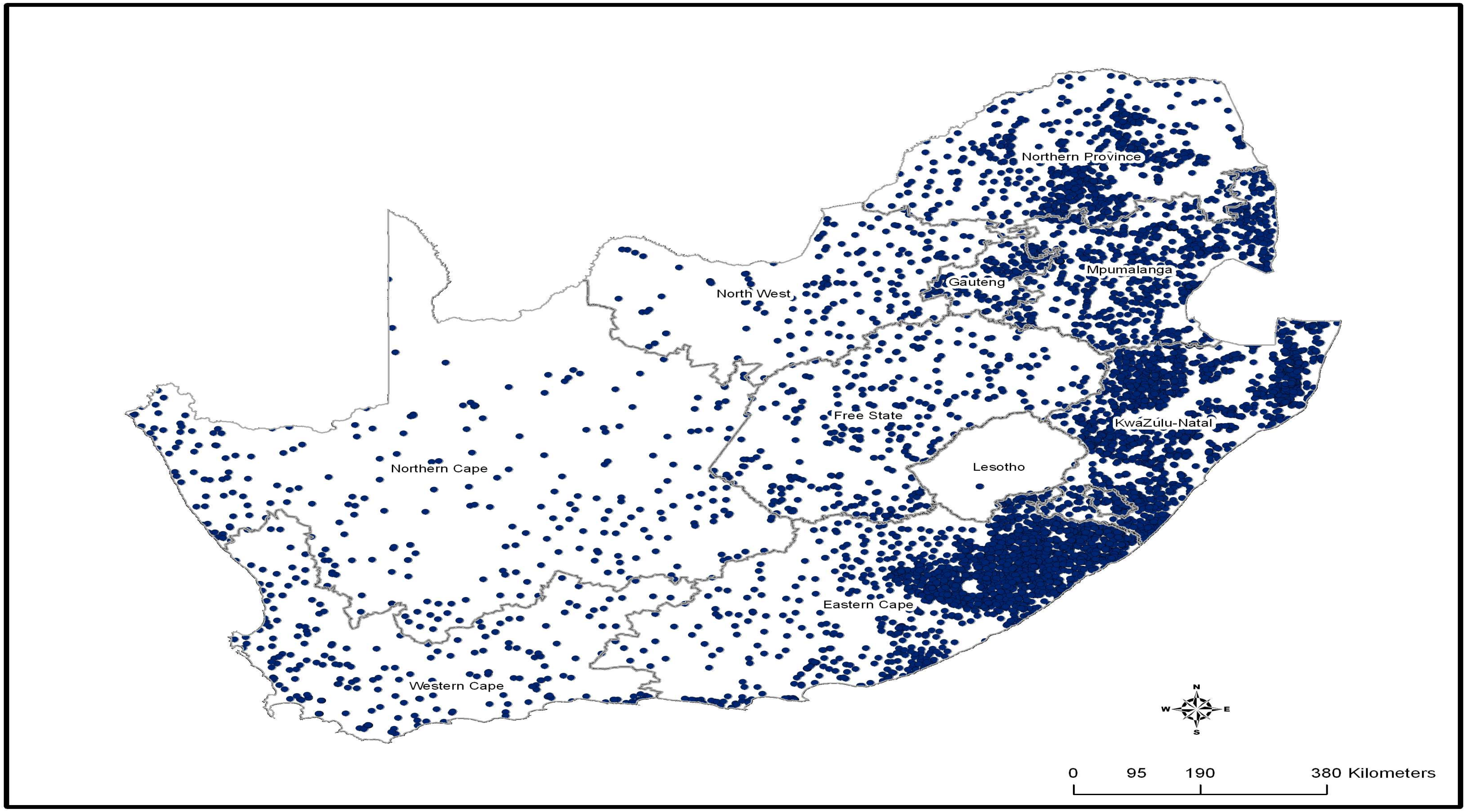


Figure 7.3 Distribution of the modal soil profiles in South Africa

The distribution of organic carbon stocks in South African soils is displayed in Figure 7.4. Most of the modal profiles in the land type survey contain 20 000 to 50 000 kg ha^{-1} of organic carbon. The inverse relationship between organic carbon stocks and number of modal profiles is evidence that South African soils do not have high organic carbon levels. This confirms the findings of Scotney & Dijkhuis (1990) who stated that South African soils have very low organic matter levels.

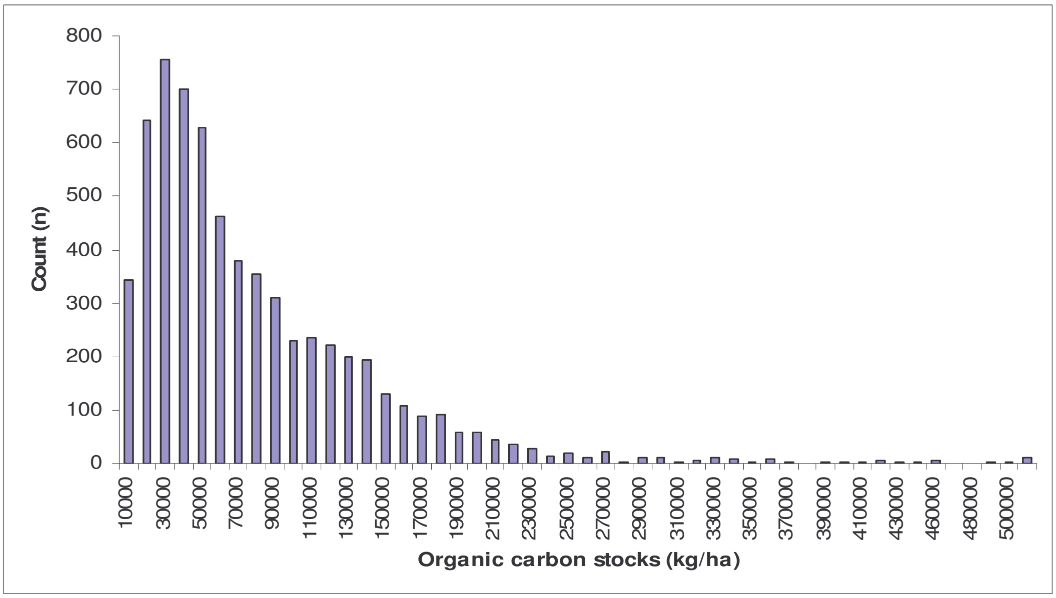


Figure 7.4 Distribution of organic carbon stocks in South African soils based on an average bulk density of 1.50 g cm^{-3}

A map of organic carbon stocks in South African soils is presented in Figure 7.5. The horizontal cross-section of this map showed that the organic carbon stocks of South African soils increased from Northern Cape province in the west to KwaZulu-Natal province in the east (Figure 7.6). Even though organic carbon content was poorly correlated with rainfall in the master (Chapter 4) and diagnostic (Chapter 5) horizons, Figure 7.5 and 7.6 revealed that organic carbon stocks in soils of South Africa increased with an increase in rainfall and a decrease in temperature.

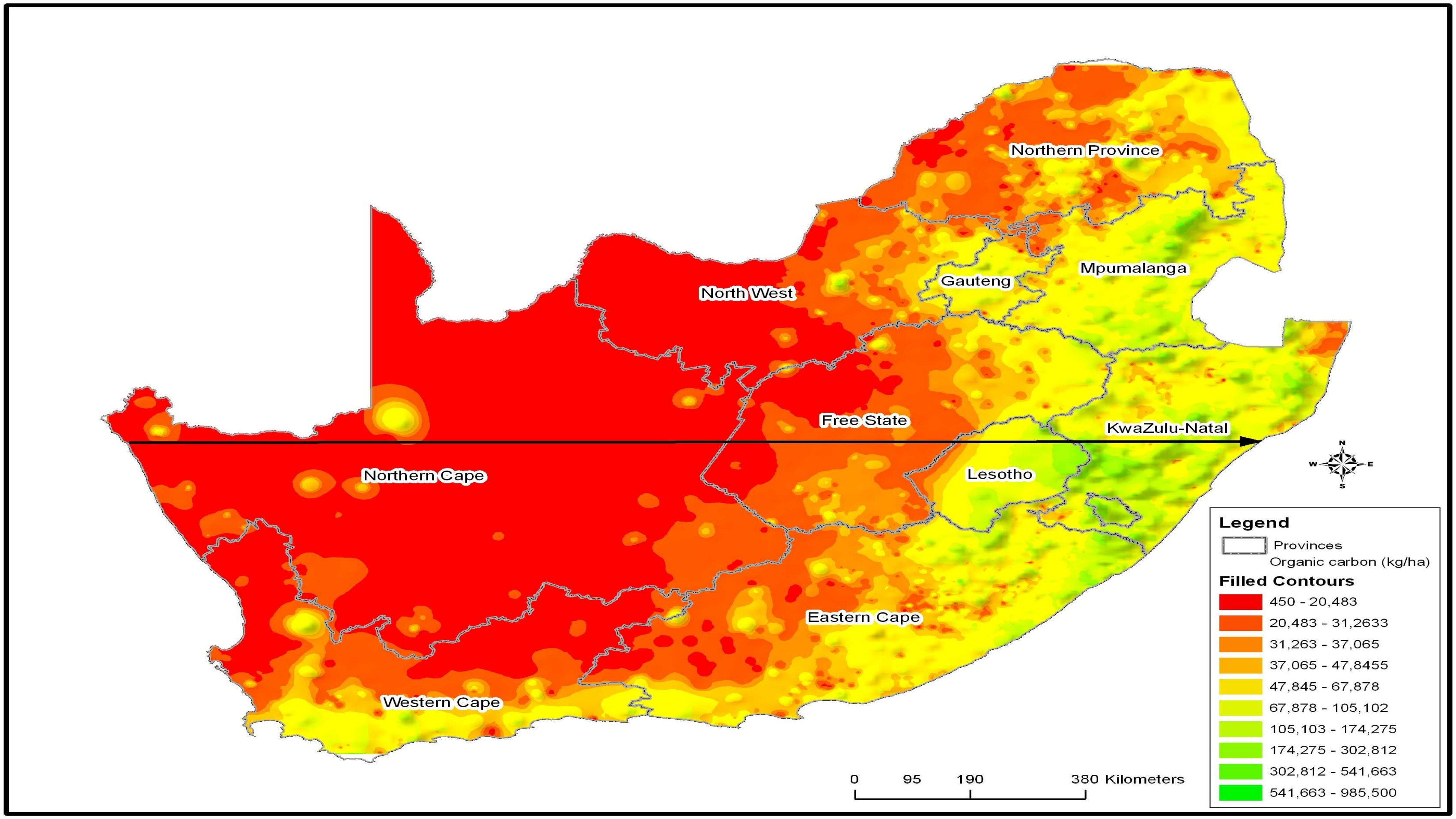


Figure 7.5 Map showing soil organic carbon stocks to 300 mm depth for South Africa

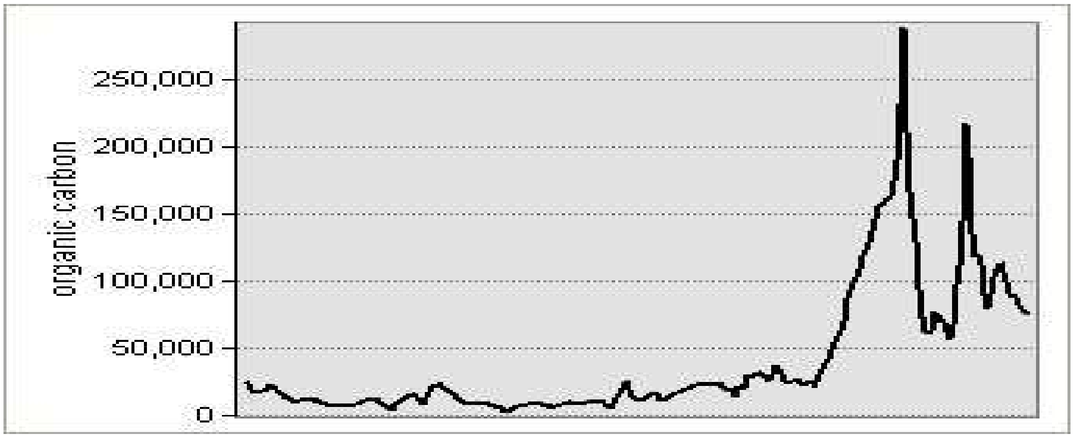


Figure 7.6 A cross-section graph of the map of soil organic carbon stocks (kg ha^{-1}) from the west (Northern Cape) to the east (KwaZulu-Natal)

However, Figure 7.7 shows that there is a positive relationship between organic carbon stocks and mean annual rainfall. Unfortunately only 27% of the variability could be explained by the model. These results confirm the findings of Barnard (2000) that the amount of organic carbon in South African topsoils followed the same trend as the pattern of the generalized rainfall map of South Africa although they were poorly correlated. The correlation coefficient he found was higher (R^2 = 0.59) than the correlation coefficient value found in this study (R^2 = 0.27). Jones *et al*. (2004a) also reported that the organic carbon content of the soils of Europe is highly related to water availability which is a function of mean annual precipitation and temperature in both virgin and cultivated soils. They found that organic carbon increased with precipitation and decreased with temperature. Generally, climate especially temperature and precipitation are the most important factors for regulating soil organic matter (Alvarez & Lavado, 1998), because it regulates the amount of vegetation cover, the quality and quantity of organic residues that are added to the soil as well as the rate of soil organic matter mineralisation and decomposition and therefore soil organic matter turnover (Hontoria *et al.,* 1999).

Organic carbon stock may have been influenced not only by climate but also factors such as parent material, topography, and land cover as well as human induced factors such as land use practices and land degradation. Barnard (2000) agrees that organic carbon followed the land cover pattern since organic matter content is positively influenced by plant cover which is in turn related to rainfall. According to Hope *et al.* (2009) the western parts of South Africa are dominated by fynbos vegetation and are susceptible to significant changes in land cover. They also add that this may be caused by the invasion of exotic trees as well as clearing, fires, and is also a result of inter annual fluctuations in rainfall which highly influence the organic carbon in the soil. Literature studies have revealed that organic carbon levels tend to drop due to practices such as burning and deforestation. On the other hand, the eastern parts like in KwaZulu-Natal province are described as perennially green with grassland. In this province about 40% of the plantations in South Africa (Dye *et al.,* 2001; De Villiers *et al.,* 2002) are found because of favourable water conditions. The vegetation tends to be luxurious especially along the coastal strip, with coastal forests (De Villiers *et al.,* 2002). This is probably why the organic carbon stock of South African soils was lower in the west and higher in the east. The amount of organic carbon increases as organic material and precipitation increases (Carter, 1996).

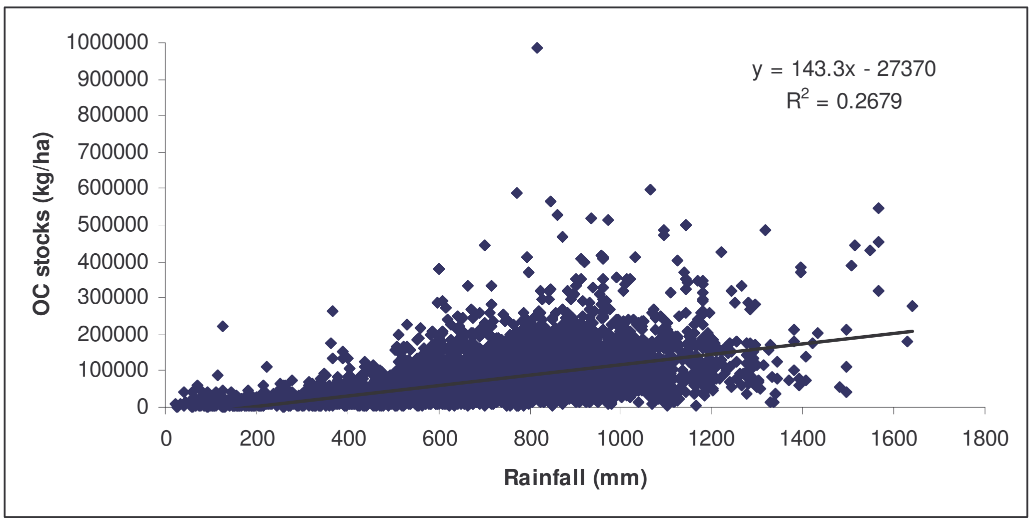


Figure 7.7 Relationship between rainfall and soil organic carbon stocks in the modal profiles

7.4 Conclusions

Reliable and accurate estimates of organic carbon stocks are needed as a baseline in order to produce and develop effective mitigation strategies that will reduce the high carbon levels in the atmosphere as well as improving the fertility status of South African soils and combating soil degradation. Models that can be used to calculate soil organic carbon stocks require known soil bulk density data which can be a constraint since most surveys do not have bulk density measurements as the determination is laborious and time-consuming.

Therefore bulk density assumptions of 1.30 g cm^{-3}, 1.50 g cm^{-3}, and 1.70 g cm^{-3} were made to calculate organic carbon stocks for the modal profiles to a depth of 300mm. Based on a bulk density of 1.50 g cm^{-3}, the average organic carbon stocks of the modal profiles is 73 726 kg ha^{-1}. The organic carbon stock in South African soils is estimated to be 8.99 ± 0.10 Pg calculated at a depth of 0.30 m. However South African soils contain 0.57% of the world's soil organic carbon stocks with South Africa covering about 0.82% of the world's total land area. Unfortunately this value cannot be used as a representative value for the carbon stocks of South Africa in relation to the world's because organic carbon is expected to decrease with depth since the world's carbon stocks were calculated to a depth of 1 m. Therefore a lower value will be expected if carbon stocks are estimated to a depth of 1 m in South Africa.

However most of the modal profiles had an organic carbon content of between 20 000 kg ha^{-1} and 50 000 kg ha^{-1}. The number of modal profiles decreased as the organic carbon stocks increased which indicated the South African soils have low organic carbon stocks. The results also revealed that the organic carbon stocks in the modal profiles increased from the warmer, drier western to the cooler, wetter parts of the country. Therefore organic carbon stocks in the modal profiles were also influenced by land cover since it is directly related to rainfall.

CHAPTER 8
ORGANIC CARBON STOCKS IN THE LAND COVER CLASSSES OF SOUTH AFRICA

8.1 Introduction

Planning of proper soil organic carbon conservation measures requires knowledge of current soil organic carbon levels as well as the factors that affect its storage. According to literature studies there are several factors that affect the levels of organic carbon in South African soils. These include natural factors such as climate, parent material, topography, and vegetation (Jenny, 1941) as well as human induced factors such as land use, management, and degradation (Jones *et al.,* 2004a). Scotney and Dijkhuis (1990) highlight climate and parent material as well as processes such as weathering as the main factors that give South African soils their diverse character.

There are different types of land use practices that differ from region to region (Helfrich *et al.*, 2006). The different land use practices not only control the magnitude of soil organic carbon stocks, but also influence the composition and quality of organic matter in soils. The change from one land use practice to another could occur naturally or through human activity, such as for food or timber production. This change can be brought about by management practices that add little organic matter to the soil or increase the rates of organic matter decomposition, thus leading to reduced levels of organic matter in the soil. The topsoil therefore becomes more prone to erosion. These activities also result in the release of C to the atmosphere. These land use practices may include crop farming, both under dryland and irrigation, stock farming, and forestry.

Tillage is often highlighted as the main cause of soil organic matter decline (Prinsloo, 1988; Scotney & Dijkhuis*,* 1990). When virgin soils are cultivated a decrease in soil organic carbon and total nitrogen contents is caused (Van Zyl & Du Preez, 1997; Helfrich *et al.,* 2006). New lower levels of organic matter are accomplished under the cultivation of natural or semi-natural areas. These levels may be as low as 30 to 60% in cultivated soils compared to their undisturbed (or virgin) equivalents (Rusco *et al.,* 2001).

Theron (1949) and later Lobe *et al.* (2001) reported that the rate of loss of soil organic matter under cultivation decreases rapidly over the years. Prinsloo *et al.* (1990) investigated the effect of present or past cultivation on nitrogen fertility in some central Free State soils with organic carbon being one of the measured parameters. They reported large losses of organic carbon from the surface layer (0-0.15 m) with the smallest being 8%. The organic carbon content to 1 m depth had declined by an average of 36%. Cultivation therefore increased the mineralisation of soil organic carbon.

As mentioned in the literature study, Qongqo and Van Antwerpen (2000) and Dominy *et al.* (2002) studied the behaviour of organic carbon in soils under sugarcane production. There was a significant loss of organic carbon content in all studied sites and this loss decreased exponentially with increasing years under sugarcane production.

The changes in the organic matter and nutrient contents of some South African irrigated soils were investigated by Du Preez and Wiltshire (1997). The samples were collected from virgin and cultivated topsoils of different soil forms. The vegetation mostly included grassland, shrubs, and trees. The years of cultivation ranged from 1 to 50 years in three irrigation schemes (Ramah, Riet River, and Vaalharts). The virgin topsoils (<200 mm depth) from all irrigation schemes had low organic matter contents, with organic carbon means of 4412 ± 185 mg kg^{-1} from Riet River, 3872 ± 322 mg kg^{-1} from Ramah and 4819 ± 318 mg kg^{-1} from Vaalharts. There was a linear increase in soil organic matter content with mean annual rainfall in the three irrigation schemes (organic C = 6.32 x rainfall + 2034; R^2 = 0.99). They attributed the variation of soil organic matter to the differences in botanical composition, basal ground cover, and biomass production which were unfortunately not documented. This shows that irrigation has the ability to offset the negative effect of cultivation.

The conservation of vegetation cover would certainly seem to be a basic requirement for maintaining soil quality in rangelands. Du Preez and Snyman (1993) reported that there is a relationship between veld condition and soil organic matter. Three veld conditions (poor, moderate, and good) were established in an experiment in a *Themeda-Cymbopogon* grassland of the Free State near Bloemfontein on a Bloemdal soil. Basal cover decreased linearly with veld condition. After 15 years, the poor and moderate veld had 25% and 16% less organic matter respectively than the good veld. A loss of 33% organic carbon in the upper 50 mm was incurred where a veld of good condition was converted to a poor veld condition. They concluded that this might have been caused by lower biomass production and greater soil temperatures in the poor and moderate veld compared to the good veld and this resulted in less organic matter being returned to the soil.

When a cultivated soil has been transformed to pasture, there is a return of nitrogen as well as organic carbon contents which is known as secondary succession (Prinsloo *et al.,* 1990). This may be caused by a decrease in aeration in pastures which decreases the rate of organic carbon loss as well as a decrease in the erodibility of the tilled layer. The effect of erosion in the absence of cultivation and enhanced vegetation cover is rather easily explained, because the exponential decrease in soil organic matter concentration with depth means that relatively little topsoil need be lost to reduce significantly the total soil organic matter content (Mills & Fey, 2003a). West and Post (2002) state that loss of soil organic carbon can be inverted by ceasing cultivation and returning to the original land cover or other perennial vegetation especially grasslands.

As a result of the changes in land use practices over the years, there has been a great addition of C to the atmosphere as carbon dioxide. However, the sequestration of C into the soil can help reduce the addition of the greenhouse gases to the atmosphere (Mestdagh *et al*., 2009). In harmony with the Kyoto Protocol, soils and vegetation can be accepted as potential C sinks and can be used to offset the emissions of green house gases (Mills *et al.,* 2003b). Prior to assessing the variations brought about by land use and climate change the present soil organic carbon stocks have to be estimated (Batjes, 2008). Since this exercise has been done in Chapter 7 it is now possible to determine the organic carbon stocks in the land cover classes of South Africa.

8.2 Procedure

The methodology applied for the estimation of carbon stocks in soils of South Africa using land type data is described in the previous chapter. This land type data was collected during a survey that started in 1970 and was founded on the theory of land types (Land Type Survey Staff, 2003). Each land type displays a certain level of uniformity in terms of terrain morphology, climate, and soil pattern. A number of soil profiles, called modal profiles were chosen to signify the range of soils encountered in the survey. The Binomial Soil Classification System for South Africa (MacVicar *et* *al.,* 1977) was used for the land type survey whilst the Taxonomical Soil Classification System for South Africa (Soil Classification Working Group, 1991) was used for the later soil surveys. Approximately 2 200 modal profiles representing 6 461 soil samples all over South Africa were sampled and analysed *inter alia* for organic carbon content, allowing thus organic carbon stock estimations. A digital national land cover map (Figure 8.1) of the CSIR (1999) was overlaid with the organic carbon stock map (Figure 7.5) and the results were presented in Table 8.1. An average for the organic carbon stocks of all the land cover classes was calculated for the estimation of the total organic carbon stock therein.

8.3 Results and discussion

8.3.1 Contribution of land cover classes to total organic carbon stock

Table 8.2 with 27 land cover classes shows in ascending contribution of the land cover classes to organic carbon stocks in South Africa. The total organic carbon stock in these classes ranged from 0.001 Pg in the urban built-upland: residential (small holdings: bushland) to 2.369 Pg in the unimproved grassland. Unfortunately there were 12 polygons of land cover classes that were not identified and they contributed 0.006 Pg which is 0.08% of the organic carbon stocks in South Africa. The barren rock (0.002 Pg) contributed a very low amount of organic carbon as well as did the mines and quarries (0.005 Pg).

The unimproved grassland contributed the highest amount of organic carbon stocks which was 33.54% of the total organic carbon probably because of higher biomass production. According to Theron (1965) the organic matter content of a soil is built up to a reasonably high level when kept under its natural grass cover. He added that it can be maintained at a stable level indefinitely as long as the vegetation is not overly disturbed. The unimproved grassland was followed by thicket and bushland with 1.401 Pg which is 19.83% of the total organic carbon in South African soils. This shows that the establishment or maintenance of a permanent vegetation cover (e.g. pasture, thicket) will maintain or increase soil organic carbon (Dominy & Haynes, 2002). Mills *et al.* (2005a) also reported the highest organic carbon stocks in the thicket and grassland sites in untransformed indigenous vegetation.

Even though the unimproved grasslands contributed a higher total organic carbon stock than the forest (0.804 Pg) and forest plantations (0.215 Pg), which contributed 11.38% and 3.05% respectively, the results differ when considering the organic carbon stocks in terms of their contribution per unit area. According to Table 8.3 the forests (114.64 Mg ha^{-1}) and forest plantations (120.21 Mg ha^{-1}) contributed more than the unimproved grasslands (91.32 Mg ha^{-1}). Jobbagy and Jackson (2000) state that forests produce woody above-ground inputs which are rather low in decomposability that is probably why the accumulation of soil organic carbon is higher in the surface soils of forests than grasslands.

However, the degraded unimproved grasslands (0.123 Pg), as well as the degraded thicket and bushland (0.121 Pg) contributed 1.75 and 1.71% of the total organic carbon stocks respectively. The other degraded areas namely shrubland and low Fynbos (0.12 Pg) as well as dongas and sheet erosion scars (0.007 Pg) contributed a lower amount of organic carbon at 0.17% and 0.10% of the total organic carbon stocks respectively. In total the degraded area covered 4.9% of the total area of South Africa. Garland *et al.* (1999) stated that erosion is one of the major forms of degradation in South Africa, and will probably be a constant problem, because an estimated 20% of the country's total area is highly erodible. Rainfall, topography, and geological characteristics are the key factors during erosion. Most of all this is a result of the low soil organic matter content (De Villiers *et al.,* 2002). This means that to combat land degradation soil organic matter levels should be improved. The degraded unimproved grasslands may be a result of activities such as overgrazing and erosion. Improper management of stock production on veld also causes low organic matter levels in the soil (Du Preez., 2000). The most important threats to thicket and bushland areas are overgrazing, medicinal plant harvesting, and urban development (McGinley, 2008).

According to Table 8.2, in the cultivated areas the temporary commercial dryland (0.413 Pg) contributed the highest organic carbon stocks followed by cultivated temporary semi-commercial/subsistence dryland (0.242 Pg). However considering their contribution per unit area, cultivated permanent commercial dryland and cultivated permanent commercial sugarcane had more organic carbon stocks (Table 8.3). Since organic carbon has been reported to decrease under cultivation a direct survey on cultivated lands is expected to reveal lower organic carbon levels because the samples for this study were taken mostly on virgin lands.

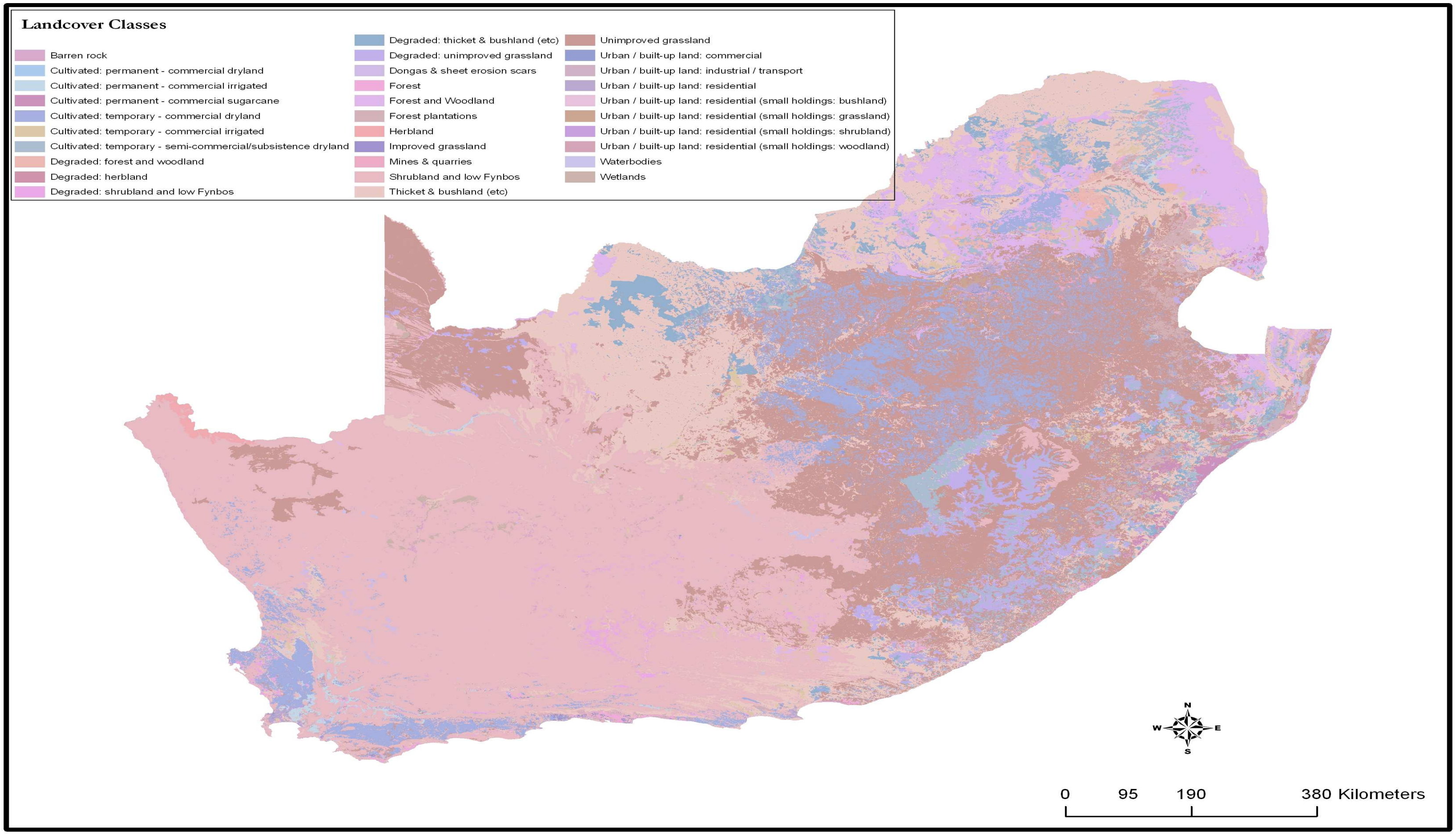


Figure 8.1 National land cover map of South Africa (CSIR, 1999)

8.3.2 Organic carbon stock per unit area in land cover classes

The organic carbon stock in the 27 land cover classes ranged from 9 Mg ha^{-1} in the barren rock to 120.21 Mg ha^{-1} in the forest plantations (Table 8.3). The unidentified land cover classes had an organic carbon stock of 17.55 Mg ha^{-1} and covered 0.3% of the land area of South Africa. The barren rock was expected to have very low organic carbon content because the penetration of roots and water is impossible except if there are cracks in the rock (Soil Classification Working Group, 1991). Therefore this does not allow the accumulation of organic material. The little organic carbon content that was able to be extracted from the rocks may probably be caused by the occurrence of calcium containing minerals which guards soil organic matter against decomposition (Sanchez *et al.,* 1989). The barren rock occupies 0.2% of South Africa's land area.

The forest plantations had the highest organic carbon stock namely 120 Mg ha^{-1} followed by forests with 114.64 Mg ha^{-1}. Gosz *et al.* (1976) stated that the most important reservoir of organic matter and nutrients is the forest floor. According to Gregorich *et al.* (2007) forests are very important because most the loss in soil organic matter occurs within 10 years after clearing of forests or native grassland, with the size of loss depending on the type of soil. This means that if forest clearing is ceased and substituted with afforestation a lot of organic carbon can be sequestered. The results found in Chapter 7, revealed that organic carbon stocks increased from the western to the eastern parts of the country. This was attributed to higher rainfall in the eastern parts of South Africa. However, De Villiers *et al.* (2002) also add that natural indigenous forests spread as far as to the east coast with KwaZulu-Natal having about 38.9% of the plantations in South Africa. This shows that perennial vegetation allows the accumulation of soil organic carbon by essentially reversing some of the effects responsible for soil organic carbon losses (Post & Kwon, 2000). The organic carbon stocks in the forests of South Africa are also high because most of them are located in the areas with higher rainfall (De Villiers *et al.,* 2002).

The wetlands had the third highest organic carbon stocks namely 105.59 Mg ha^{-1}. A lot of organic carbon was expected from wetlands since these are areas made up of extensive deposits of peat (Masupa *et al.,* 2008). Masupa *et al.* (2008) also add that these organic rich soils which are basically formed in constantly saturated wetlands are very rare in South Africa. According to the results these areas cover 0.5% of

South Africa's land area. Unfortunately, wetlands have been threatened by pollution, overgrazing or imprudent cultivation in the sponge areas and in the upper catchments of rivers (De Villiers *et al.* 2002; Masupa *et al.,* 2008). If these threats are not attended to, the organic carbon stocks in the wetlands will probably decline. The waterbodies had an average organic carbon stock of 53.91 Mg ha^{-1} and cover 0.4% of the land area of South Africa.

Among all the cultivated areas the permanent commercial dryland had the highest organic carbon stock of 97.73 Mg ha^{-1} followed by the permanent commercial sugarcane with 91.56 Mg ha^{-1}. The former practice covers 0.1% and the latter covers 0.4% of the area of South Africa. The permanent commercial dryland had higher organic carbon stocks than the cultivated permanent commercial irrigated land (47.30 Mg ha^{-1}) even though the former (0.1%) covers a smaller area than the latter (0.3%). Irrigated land was not expected to have a lower organic carbon stock because more plant biomass production was expected due to increased water content. Increased plant productivity results in more organic material (Carter, 1996). Since the samples for this research were taken from virgin lands, the present organic carbon stocks on cultivated lands are expected to be lower. This is because research has shown a great decline in organic carbon due to cultivation (Scotney & Dijkhuis, 1990; Tate, 1992b; Du Toit *et al.,* 1994; Du Preez & Wiltshire, 1997). According to Theron (1965) it is quite impossible to maintain the organic matter content of the soil, especially under normal dryland cultivation especially during the first years of cultivation.

The organic carbon stocks on cultivated permanent commercial dryland were probably high because conservation tillage may have been practiced in those areas. The retention of crop residues on or near the soil surface (Graham *et al.,* 2002), which is commonly referred to as conservation tillage, may have helped to improve soil organic carbon levels. Van der Watt (1987) reported an increase of 38% in organic carbon content of the top layer under stubble-mulch tillage when compared with conventional tillage. Temporary commercial dryland occupies the largest cultivation area (8%) and the lowest organic carbon stock of 42.38 Mg ha^{-1} among the cultivated areas.

The area cultivated permanently with sugarcane (0.4%) had an organic carbon stock of 91.56 Mg ha^{-1}. The results of Qongqo and Van Antwerpen (2000) as well as Dominy *et al.* (2002) identified losses in soil organic matter in soils cultivated with sugarcane. Their results revealed that as the period of cultivation increased there was a decrease in organic matter. This means that the organic carbon stock in the sugarcane lands is probably lower than estimated in this study. However Van Antwerpen and Meyer (1996) earlier reported that irrigated areas under sugarcane production in northern KwaZulu-Natal lost more organic matter than the dryland areas. The loss was accredited to the practice of burning cane before harvest under the monocultural system of sugarcane production in South Africa, leading to increased soil degradation. However, Van Antwerpen *et al.* (2002) reported that green cane harvesting with trash retention has the potential of conserving soil organic carbon even though this can vary depending on the variability of rainfall.

Among the urban built-up lands, the area used for industry and transport (94.50 Mg ha^{-1}) had higher organic carbon stocks than the urban residential (59.81 Mg ha^{-1}), urban residential small holdings: grassland (53.40 Mg ha^{-1}), and residential small holdings: bushland (24.75 Mg ha^{-1}). The grassland area probably had higher organic carbon stocks than the bushland because of a higher biomass production under grassland vegetation and less microbial activity due to less aeration.

Table 8.1 Organic carbon stocks in the different land cover classes of South Africa

Description	Area		Organic carbon		
	(ha)	(%)	(Pg)	(Mg ha^{-1})	(%)
Barren rock	260361	0.2	0.002	9.00	0.03
Cultivated: permanent – commercial dryland	83067	0.1	0.008	97.73	0.11
Cultivated: permanent – commercial irrigated	416753	0.3	0.020	47.30	0.28
Cultivated: permanent – commercial sugarcane	459370	0.4	0.042	91.56	0.60
Cultivated: temporary – commercial dryland	9748151	8.0	0.413	42.38	5.85
Cultivated: temporary – commercial irrigated	1081257	0.9	0.064	59.36	0.91
Cultivated: temporary – semi-commercial/subsistence dryland	2964631	2.4	0.242	81.69	3.43
Degraded: forest and woodland	965723	0.8	0.031	32.44	0.44
Degraded: shrubland and low Fynbos	563182	0.5	0.012	21.75	0.17
Degraded: thicket and bushland (etc)	2256032	1.9	0.121	53.63	1.71
Degraded: unimproved grassland	1862584	1.5	0.123	66.25	1.75
Dongas and sheet erosion scars	186514	0.2	0.007	38.12	0.10
Forest	7011196	5.8	0.804	114.64	11.38
Forest and Woodland	401370	0.3	0.025	63.30	0.36
Forest plantations	1790270	1.5	0.215	120.21	3.05
Improved grassland	128203	0.1	0.007	58.14	0.11
Mines and quarries	175421	0.1	0.005	29.81	0.07

Table 8.1 Continued …

Description	Area		Organic carbon		
	(ha)	(%)	(Pg)	(Mg ha^{-1})	(%)
Shrubland and low Fynbos	41514274	34.1	0.981	23.62	13.88
Thicket and bushland (etc)	21409243	17.6	1.401	65.43	19.83
Unimproved grassland	25945427	21.3	2.369	91.32	33.54
Urban / built-up land: industrial / transport	64652	0.1	0.006	94.50	0.09
Urban / built-up land: residential	1084164	0.9	0.065	59.81	0.92
Urban / built-up land: residential (small holdings: bushland)	27928	0.0	0.001	24.75	0.01
Urban / built-up land: residential (small holdings: grassland)	134927	0.1	0.007	53.40	0.10
Waterbodies	460959	0.4	0.025	53.91	0.35
Wetlands	581737	0.5	0.061	105.59	0.87
Unidentified land cover classes	330393	0.3	0.006	17.55	0.08
Total	121907789	100	7.065	1617.20	100

Table 8.2 Contribution of land cover classes to total organic carbon stock in ascending order

Land cover class	Organic carbon	
	Pg	%
Urban / built-up land: residential (small holdings: bushland)	0.001	0.01
Barren rock	0.002	0.03
Mines & quarries	0.005	0.07
Unidentified land cover classes	0.006	0.08
Urban / built-up land: industrial / transport	0.006	0.09
Dongas & sheet erosion scars	0.007	0.10
Urban / built-up land: residential (small holdings: grassland)	0.007	0.10
Improved grassland	0.007	0.11
Cultivated: permanent - commercial dryland	0.008	0.11
Degraded: shrubland and low Fynbos	0.012	0.17
Cultivated: permanent - commercial irrigated	0.020	0.28
Waterbodies	0.025	0.35
Forest and Woodland	0.025	0.36
Degraded: forest and woodland	0.031	0.44
Cultivated: permanent - commercial sugarcane	0.042	0.60
Wetlands	0.061	0.87
Cultivated: temporary - commercial irrigated	0.064	0.91
Urban / built-up land: residential	0.065	0.92
Degraded: thicket & bushland (etc)	0.121	1.71
Degraded: unimproved grassland	0.123	1.75
Forest plantations	0.215	3.05
Cultivated: temporary - semi-commercial/subsistence dryland	0.242	3.43
Cultivated: temporary - commercial dryland	0.413	5.85
Forest	0.804	11.38
Shrubland and low Fynbos	0.981	13.88
Thicket & bushland (etc)	1.401	19.83
Unimproved grassland	2.369	33.54
Total	7.065	100

Table 8.3 Organic carbon stock in ascending order per unit area in the land cover classes

Land cover class	Organic carbon content (Mg ha^{-1})
Barren rock	9.00
Unidentified land cover classes	17.55
Degraded: shrubland and low Fynbos	21.75
Shrubland and low Fynbos	23.62
Urban / built-up land: residential (small holdings: bushland)	24.75
Mines & quarries	29.81
Degraded: forest and woodland	32.44
Dongas & sheet erosion scars	38.12
Cultivated: temporary - commercial dryland	42.38
Cultivated: permanent - commercial irrigated	47.30
Urban / built-up land: residential (small holdings: grassland)	53.40
Degraded: thicket & bushland (etc)	53.63
Waterbodies	53.91
Improved grassland	58.14
Cultivated: temporary - commercial irrigated	59.36
Urban / built-up land: residential	59.81
Forest and Woodland	63.30
Thicket & bushland (etc)	65.43
Degraded: unimproved grassland	66.25
Cultivated: temporary - semi-commercial/subsistence dryland	81.69
Unimproved grassland	91.32
Cultivated: permanent - commercial sugarcane	91.56
Urban / built-up land: industrial / transport	94.50
Cultivated: permanent - commercial dryland	97.73
Wetlands	105.59
Forest	114.64
Forest plantations	120.21

8.4 Conclusions

The distribution of soil organic carbon stocks varied depending on the type of vegetation on the land or the land use practice. However, the sequestration of carbon can be attained after the conversion of intensely agricultural cropping to extensive land use practices such as afforestation and natural succession ecosystems (Degryze *et al.,* 2004). According to this study the highest accumulation of organic carbon per unit area in South African soils was found in the forests plantations > forests > wetlands. However the biggest contribution to the total organic carbon stocks, was reported in the unimproved grassland > thicket and bushland > shrubland and low Fynbos > forests. The conversion of cultivated marginal lands and degraded areas to perennial pastures and forest plantations can help in carbon sequestration. This means that by improving the management practices of these areas, soils and vegetation can be used as carbon sinks especially under the Kyoto Protocol where soil organic carbon is very important in the global carbon sink. Measures should therefore be taken to rehabilitate the degraded forest and woodlands by afforestation, reseeding of degraded rangelands and unimproved grasslands which will result in more organic carbon stocks. Wetlands should also be protected to prevent overgrazing and those that have been damaged should be repaired using soil and water conservation measures. Rehabilitation of dongas and sheet erosion scars should be put in place as these will in turn help conserve more organic carbon. Cultivation of marginal lands should also be prohibited.

Among all the cultivated areas, the cultivated permanent commercial dryland had the highest organic carbon stocks per unit area. Therefore mitigation strategies such as conservation tillage, which involve: retaining crop residues on or near the soil surface, practicing crop rotation and using organic fertilisers may help improve the accumulation of soil organic carbon in the soil.

CHAPTER 9
SUMMARY AND RECOMMENDATIONS

9.1 Summary

Organic carbon is a very important component in the soil. This is because it plays a vital role in soil fertility. Organic carbon can be lost in the soil by practices such as cultivation especially on marginal lands, overgrazing, soil erosion, and deforestation. Some of these practices have contributed highly to the release of carbon to the atmosphere. Unfortunately, South African soils have been plagued by low organic carbon levels. Since soils are important carbon dioxide sinks, the removal of carbon dioxide from the atmosphere to the soil as well as the changes in carbon content associated with changes in land use practices should be investigated. Prior to that, baseline data on the current organic carbon stocks should be available. This has not been done for South African soils. It is therefore important to estimate the current organic carbon stocks in South African soils as well as the factors that affect it.

The main objective of this study was to quantify organic carbon stocks in South African soils using existing data with reference to master horizons, diagnostic horizons, soil forms, and land cover classes. Added to that, the amount of organic carbon was related to soil forming factors namely: climate (rainfall, evaporation, and aridity index) as well as topography (terrain morphological units, slope percentage, slope type, and slope aspect) and soil texture (clay content).

The data used in this study was taken from the land type survey which started in 1970 with samples taken from all over South Africa. Approximately 2 200 modal profiles representing 6 461 samples were analysed for physical and chemical properties including organic carbon. The data was captured in a MS Access database by the ARC-Institute for Soil, Climate and Water in Pretoria. The main emphasis in this study was put on the parameters that affect the level of organic carbon in soil. The land type survey data was structured per master horizon and per diagnostic horizon. The relationship between organic carbon and the other parameters namely: rainfall, evaporation, aridity index, clay percentage, terrain morphological unit, slope percentage, slope aspect, and slope type was investigated. A regression was done to study the correlation per master and diagnostic horizon between the dependent variable which is organic carbon and the independent variables namely: rainfall, evaporation, slope aspect, aridity index, and clay.

The results revealed that there was great variation in organic carbon content in the master horizons of South African soils. The organic carbon content in these horizons decreased as follows: O, A, R, G, B, E, and C horizons and ranged on average from 15.98% in the O horizon to 0.27% in the C horizons. However, the surface horizons (O and A) seemed to have accumulated more organic carbon than all the other master horizons with the O horizon having a significantly higher organic carbon content. According to some literature, organic carbon decreases with depth and tends to accumulate in the topsoils because of more vegetative production at the surface.

In the diagnostic horizons the highest organic carbon was recorded in the topsoils and ranged on average from 20.89% in the organic O to 1.41% in the orthic A horizons. The organic carbon content in the diagnostic subsoil horizons ranged on average from 1.18% in the podzol B to 0.15% in the dorbank B horizons.

Unfortunately, the relationship between organic carbon and rainfall, evaporation, and aridity index was very weak in both the master and diagnostic horizons. Most of the correlation coefficients were low. The effect of rainfall, evaporation, and aridity index was therefore not conclusive.

For the master horizons, soil organic carbon content related positively to rainfall and aridity index in the A, E, B, G, C, and R horizons, but was negatively correlated with evaporation. The opposite was experienced in the O horizon. A positive relationship between organic carbon and rainfall was found in the pedocutanic B, prismacutanic B, soft plinthic B, red apedal B, yellow-brown apedal B, red structured B, G, unspecified material with signs of wetness, E, neocarbonate B, neocutanic B, regic sand, stratified alluvium, lithocutanic B, hard rock, unconsolidated material without signs of wetness, unspecified dry material, and saprolite. The relationship between organic carbon and evaporation was negative in those diagnostic horizons. Rainfall and aridity index related negatively with organic carbon content and positively with evaporation in the following diagnostic horizons: soft carbonate B, podzol B, hard plinthic B, saprolite, and unconsolidated material with signs of wetness.

Topography affected the amount of organic carbon in the master and diagnostic horizons and also influenced the formation of other horizons. All the master horizons were found at the midslopes except the O horizon. All of them were found on the footslopes. The highest amount of organic carbon was found in the O horizons which were restricted to the footslopes and valley bottom. The G horizons at the valley bottom also had the highest organic carbon content. The A and E horizons on the upper midslopes recorded the highest organic carbon content. However, only the O and G horizons had high organic carbon contents at almost level areas, whereas the organic carbon contents in the A, E, B, and C horizons generally increased with an increase in slope to approximately 10%. The pattern became vague as slope percentage increased. Horizons such as the O horizon were never found at slopes greater than 2%. The R horizon was limited to slopes ranging from 1 to 3% while the G horizon occurred mostly at slopes of 1 to 8% and rarely at slopes of 9 to 20%.

In the diagnostic horizons, the highest organic carbon content was mostly found at the footslopes, lower footslopes, upper footslopes, midslopes, and valley bottom. The terrain of an area also restricted the formation of some diagnostic horizons. The yellow-brown apedal B horizons were only found at the valley bottom while the organic O was found at the valley bottom and footslopes.

The highest organic carbon content was found in lower slope percentages in the organic O, humic A, vertic A, soft carbonate B, podzol B, soft plinthic B, hard plinthic B, red structured B, G horizon, unconsolidated material with signs of wetness, unspecified material with signs of wetness, gleycutanic B, neocutanic B, stratified alluvium, regic sand, hard rock, unconsolidated material without signs of wetness, and saprolite. The highest organic carbon content in the melanic A, orthic A, dorbank B, pedocutanic B, prismacutanic B, red apedal B, yellow-brown apedal B, E, and lithocutanic B horizons was found on the upper slopes. Some diagnostic horizons were restricted to certain slopes *e.g.* the organic O horizon was found at slopes < 3%, humic A < 35%, and vertic A < 10%.

The highest organic carbon content in the A and E horizons was found on the convex shaped slopes. The B and C horizons on the straight slopes had the highest organic carbon content, but most of them were formed on convex and straight slopes respectively. The O and G horizons on the concave slopes had the highest amount of organic carbon, where most of these horizons occurred. The R horizons on straight slopes had the highest organic carbon content and most of them were found on convex and straight slopes. Highest organic carbon content was on the eastern slopes for the A and C horizons, on the southern slopes for the B horizons, south eastern slopes for the E and G horizons, level slopes for the O horizon, and on the western slopes for the R horizon.

The organic O and humic A had the highest organic carbon content in the horizons found on concave slopes. The other three topsoil horizons: vertic A, melanic A, and orthic A followed the same pattern in their formation in the landscape whereby the highest organic carbon content was found on the convex slopes and the lowest on straight slopes. The convex slopes had the highest organic carbon content in the following horizons: pedocutanic B, prismacutanic B, soft plinthic B, red apedal B, neocutanic B, regic sand, G, and E horizons. However, the convex slopes had the lowest organic carbon contents for the hard plinthic B and the unspecified material with signs of wetness. The concave shaped slopes offered the best conditions for the accumulation of organic carbon in soils with hard plinthic B, yellow-brown apedal B, red structured B, unconsolidated material with signs of wetness, unspecified material with signs of wetness, and lithocutanic B horizons. On the contrary, the lowest organic carbon content on concave slopes was in the podzol B, soft plinthic B, red apedal B, G horizon, gleycutanic B, E, regic sand, stratified alluvium, hard rock, saprolite, and unconsolidated and unspecified dry materials. The highest organic carbon content on straight slopes was found in the podzol B, gleycutanic B, stratified alluvium, saprolite, and unconsolidated material with signs of wetness. The lowest was in the prismacutanic B, yellow-brown apedal B, red structured B, unconsolidated material with signs of wetness, neocutanic B, and lithocutanic B horizons. The formation of some diagnostic horizons was restricted to some slope types. The dorbank B was only found on straight slopes, the soft carbonate B horizon on convex slopes only, yellow-brown apedal B on straight and concave slopes and the unconsolidated material with signs of wetness on straight and concave slopes only.

The organic O horizon on level slopes had the highest organic carbon content in the diagnostic horizons. The highest organic carbon content in the unspecified material with signs of wetness was also on level slopes. The southerly and easterly slopes also had a positive influence on the accumulation of organic carbon in the dorbank, gleycutanic B, E, neocutanic B, regic sand, stratified alluvium, lithocutanic B, hard rock, unconsolidated material without signs of wetness, and unspecified dry material. The northerly and westerly slopes favoured the accumulation of organic carbon in the humic A, melanic A, soft carbonate B, prismacutanic B, podzol B, hard plinthic B, red apedal B, yellow-brown apedal B, and G horizons, as well as saprolite.

The correlation between organic carbon content and clay content in the master and diagnostic horizons was very low. The correlation coefficients in the master horizons ranged from 0.44 in the O to 0.003 in the G horizon. In the diagnostic horizons the correlation coefficients ranged from 0.01 in the lithocutanic B and podzol B horizons to 1 in the dorbank B horizons. The high correlation coefficients were a result of fewer observations. Clay content and organic carbon related positively in most diagnostic horizons except in the organic O, vertic A, soft carbonate B, hard plinthic B, and G horizons.

Multiple regression models with different combinations of rainfall, evaporation, aridity index, clay, slope percentage, and slope aspect could explain 50% and 100% variability in the A and O horizons respectively whilst only 3% to 55% could be explained in the remaining subsurface master horizons. About 2% to 100% variability was explained by the multiple regression models in the diagnostic horizons. The highest correlations were in the organic O topsoil, and the silicic and calcic subsoils where $R^2 = 1$ in both horizons. A variability of 75% was also explained in the podzolic soils. The rest of the correlation coefficients were low.

Soil organic carbon in the soil forms behaved in the same manner as their diagnostic topsoils. The environmental conditions such as water content and temperature that influenced the amount of organic carbon in the topsoils also determined the amount of organic carbon in the diagnostic subsoil horizons of that specific soil form. For example, the organic carbon content of the lithocutanic B horizon of the Nomanci form had a higher organic carbon content than in the Mayo form which was higher than in the Glenrosa form.

Unfortunately the correlations between organic carbon and climate, topography, and clay were very low. These variables could therefore not be used to estimate organic carbon stocks in South African soils. Organic carbon stocks were then estimated using an equation with soil bulk density, organic carbon content, depth, and area as inputs. Three bulk density values were used: low = 1.30 g cm^{-3}, average = 1.50 g cm^{-3} and high = 1.70 g cm^{-3} to represent the bulk density of South African soils.

The results revealed that the organic carbon stocks of the modal profiles of South African soils increased from the warmer, drier western to the cooler, wetter eastern parts of the country. Organic carbon also followed the trend taken by rainfall which means that soil organic carbon increased with the availability of water. Organic carbon stocks were also directly proportional to plant cover since plant cover increases with rainfall and highly influences the build up of soil organic matter. Soil organic carbon stocks ranged from 450 kg ha^{-1} to 985 500 kg ha^{-1} when calculated using the average soil bulk density of South African soils which is 1.50 g cm^{-3}. Most of the profiles had an organic carbon content of 30 000 kg ha^{-1} to 50 000 kg ha^{-1}. The number of modal profiles decreased as the organic carbon stocks increased which indicated that South African soils have low organic carbon stocks. The organic carbon stock in South African soils is estimated to be 8.99 ± 0.10 Pg calculated to a depth of 0.30 m. However South African soils contain 0.57% of the world's soil organic carbon stocks with South Africa covering about 0.82% of the world's total land area. Unfortunately this value cannot be used as a representative value for the carbon stocks of South Africa in relation to the world because organic carbon is expected to decrease with depth since the world's carbon stocks were calculated to a depth of 1 m. Therefore a lower value will be expected if carbon stocks are estimated to a depth of 1 m in South Africa.

The organic carbon stock in the 27 land cover classes ranged from 9 Mg ha^{-1} in the barren rock to 120.21 Mg ha^{-1} in the forest plantations. The forest plantations were followed by forests with 114.64 Mg ha^{-1}. The third highest organic carbon stocks were found in the wetlands (105.59 Mg ha^{-1}). Among all the cultivated areas the permanent commercial dryland had the highest organic carbon stock of 97.73 Mg ha^{-1} followed by the permanent commercial sugarcane with 91.56 Mg ha^{-1}. According to this study the highest accumulation of organic carbon per unit area in South African soils was found in the forests plantations > forests > wetlands. However the biggest contribution to the total organic carbon stocks, was reported in the unimproved grassland > thicket and bushland > shrubland and low Fynbos > forests.

The biggest area of land in South Africa is covered by shrubland and low fynbos, followed by unimproved grassland, and thicket and bushland. The degraded lands cover 4.9% of the total area. Measures should be taken to rehabilitate the degraded forest and woodlands by afforestation, improve areas with shrubland and low fynbos, thicket and bushland, reseeding of degraded rangelands and unimproved grasslands which will result in more organic carbon stocks. Soil and water conservation measures that involve rehabilitation of dongas and sheet erosion scars are should be encouraged to conserve more organic carbon. Marginal lands should not be cultivated.

9.2 Recommendations

- Soil organic carbon should be included as a compulsory analytical parameter in every study since it is very important in determining the fertility status of soil.

- Study areas (cultivated soils and virgin soils) should be dermacated and their soil organic carbon levels should be monitored over a certain period of time.

- An extensive study on soil bulk densities of South African soils should be done as it is a prerequisite for calculating soil organic carbon stocks. A database on the soil bulk density should be made.

- The temperature factor should be included in future when exploring the effect of climate on soil organic carbon content.

- Conservational tillage practices that contribute to increasing soil organic carbon such as crop rotation, use of cover crops, perennial vegetation, reseeding of degraded areas, and preventing overgrazing should be compulsory. Cultivation of marginal lands should be prohibited.

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