THE EFFECT OF PINEAPPLE CULTIVATION ON FACTORS INFLUENCING SOIL ERODIBILITY IN THE EASTERN CAPE, SOUTH AFRICA.

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ABSTRACT

The study examines the effect of ridged pineapple cultivation on factors influencing the soil erodibility of Glenrosa and Oakleaf soil forms in the Bathurst district of South Africa. A number of physical and chemical variables influencing soil erodibility are investigated, namely soil moisture, bulk density, porosity, infiltration rate, aggregate stability, shear strength, soil texture, soil structure, penetrability, organic carbon, pH and cation exchange capacity. These soil characteristics are examined in undisturbed soils under natural vegetation and compared to those on adjacent traffic areas, pineapple ridges and pineapple furrows. The results of the analyses between the four sample sites indicate that ridged cultivation of pineapples has a negative effect on factors influencing soil erodibility on the areas studied. The results of the analysis within each of the sample sites do not illustrate any clear relationships and thus depict the complexity and multiplicity of the soil erodibility phenomenon. A further study, augmenting the soil erodibility data with actual soil loss data, is recommended.

ACKNOWLEDGEMENTS

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Special thanks must go to my best friend, Mr Kim Hodgson, for being such a willing field assistant and companion who provided me with a great deal of encouragement and motivation.

Finally, I would like to dedicate this thesis to my parents as a gesture of my thanks for their constant support and belief in me.

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CHAPTER 1
INTRODUCTION

1.1 THEME

The pineapple industry, although a relatively young industry, provides a major source of agricultural income in the Bathurst district in the eastern Cape province of South Africa. Approximately 3750 ha are under production with average yields of 55 $t.ha^{-1}$ (Hill, 1991). The rolling topography of the coastal plain, the low incidence of frost and the moderate rainfall (600-700 mm per annum) make the coastal regions of the eastern Cape, between East London and Alexandria, ideal for growing pineapples. However, steep topography, shallow and highly erodible soils and high intensity rainfall often combine to result in soil erosion. The situation is aggravated by many of the soil cultivation practices adopted for pineapple cultivation (Kieck,1984). Results of rainfall simulator studies show a threefold increase in soil erosion from areas where the lands have been ridged in preparation for new pineapple plantings compared to normal unridged tillage (Kieck, 1984).

While research has been conducted to determine the impacts of pineapple cultivation on soil erosion, no reports could be found within the literature that investigate the effects of pineapple cultivation on soil erodibility. Soil erodibility is defined as the resistance of the soil to both detachment and transport (Morgan,1986). This study investigates the changes that occur to the factors thought to control soil erodibility as a consequence of cultivation. The study researches the differences in factors influencing soil erodibility between traffic areas, ridges, furrows and undisturbed soil under natural vegetation in the pineapple growing area of Bathurst. The study is conducted on areas with Glenrosa and Oakleaf soil forms which are the predominant soils of the study area. The study therefore attempts to improve the current understanding of the processes that affect soil erodibility in the pineapple lands and to recommend ways of reducing the amount of soil erosion.

1.2 RESEARCH FRAMEWORK

The research framework is presented by way of a problem definition. Since any problem is by its nature an unanswered question, posing a question is an accepted scientific method of stating a problem (Haring and Lounsbury, 1983). The key question to this thesis is:

"What effect does pineapple cultivation have on the factors affecting soil erodibility of representative soils in the pineapple growing region of Bathurst, eastern Cape?"

Conceptually, the approach adopted is to compare areas under pineapple cultivation to a natural reference state. Thus, areas with similar climatic, physiographic and soil types are compared under different management practices. The factors influencing soil erodibility which are examined in the thesis were selected on the basis of the literature review (Chapter 2 and 3). These factors include soil moisture, bulk density, porosity, infiltration rate, aggregate stability, shear strength, soil texture, soil structure, penetrability, organic carbon, pH and cation exchange capacity.

The current research set out to investigate the impact of pineapple cultivation on the factors controlling soil erodibility. In particular, the aim of the study is to investigate differences in factors affecting soil erodibility between:

1. Traffic areas adjacent to the pineapple lands
2. Pineapple ridges
3. Pineapple furrows
4. Undisturbed soil under natural vegetation

(Figures 1.1 and 1.2)

The objective of the study is therefore to quantify the effect of pineapple cultivation on the factors affecting soil erodibility of representative soils in the pineapple growing regions of Bathurst, Eastern Cape.

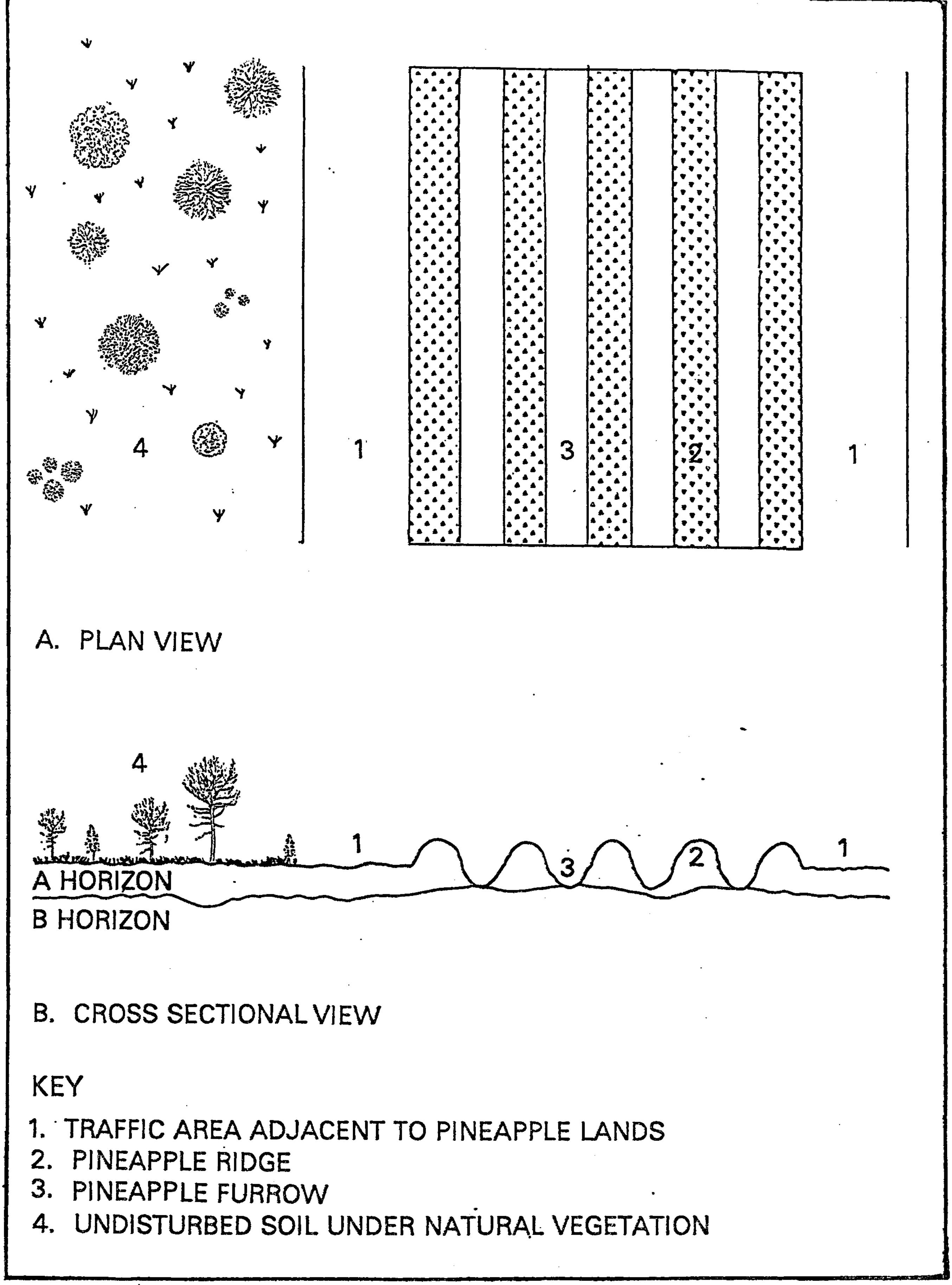

FIGURE 1.1: Different study sites found within areas of pineapple cultivation

KEY

1. Traffic area adjacent to pineapple lands
2. Pineapple ridges
3. Pineapple furrows
4. Undisturbed soil under natural vegetation

FIGURE 1.2a: Study sites in the Glenrosa soil form

KEY

1. Traffic area adjacent to pineapple lands
2. Pineapple ridges
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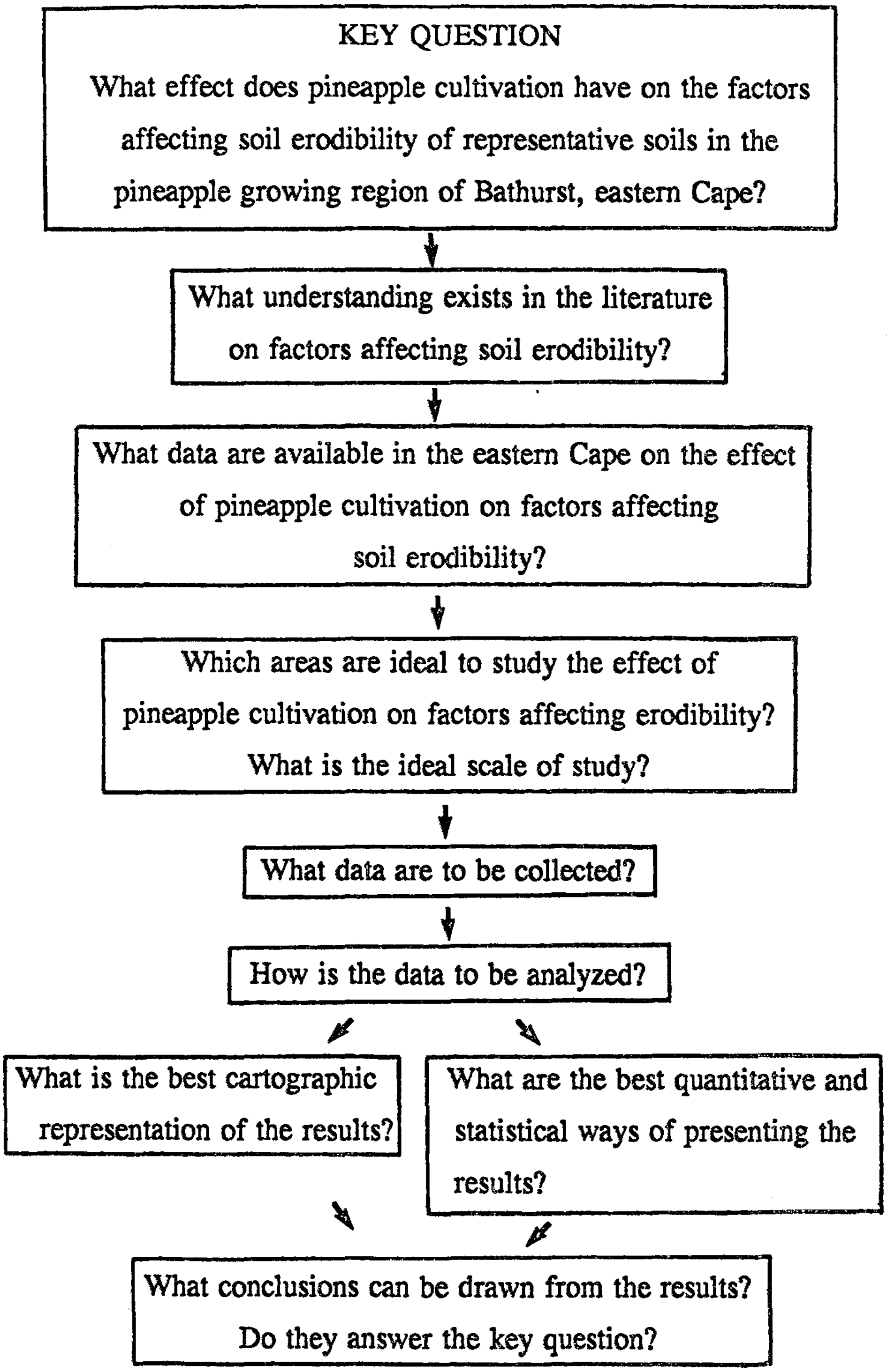
FIGURE 1.2b: Study sites in the Oakleaf soil form

Figure 1.3 outlines the sequence of questions that need to be addressed in the research programme.



(Modified from Haring and Lounsbury, 1983)

FIGURE 1.3: Key questions

1.3 THE STUDY AREA

The study area selected was on the farm 'Rosslyn' belonging to Mr B. Purdon. The farm is situated approximately 25 kilometres from Grahamstown. The grid reference is 33° 22'S and 26° 31'E (Figure 1.4).

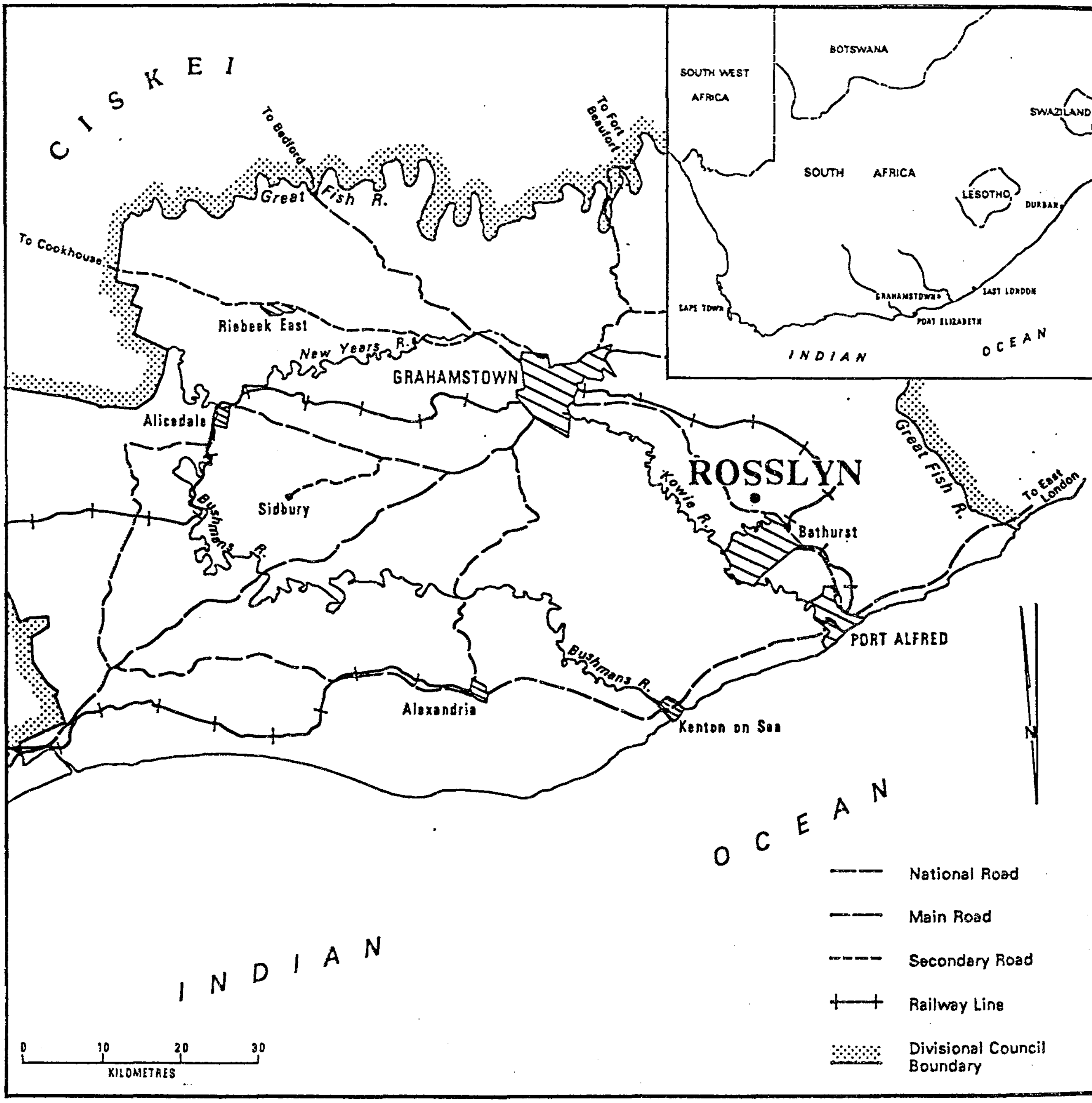


FIGURE 1.4: Location of Rosslyn

Using soil maps provided by the Bathurst Agricultural Research Station, two separate study areas were designated. A Glenrosa and an Oakleaf soil form were selected since Hill (1991) stated that these are the two soil forms in the Bathurst area of the Eastern Cape on which 60% of all pineapple cultivation occurs.

Since 95% of all pineapples grown in the Eastern Cape are cayennes, the cultivation of the cultivar of *Ananas comosus* (L) *Merr.* was investigated. Within each of the soil forms selected, four study sites were chosen:

1. Traffic area adjacent to the pineapple lands;
2. Pineapple ridges;
3. Pineapple furrows;
4. Undisturbed soil under natural vegetation (areas which had not been cultivated for a period of at least 10 years).

Care was taken to ensure that, within each soil form, the traffic, ridge, furrow and natural vegetation sites were located as close to each other as possible, contained the same soil types (Glenrosa Kilspindie or Oakleaf Ritchie), same slope steepness (Glenrosa - 4° or Oakleaf - 3°) and slope aspect (Glenrosa - NE or Oakleaf - SW). The essential difference between the four study sites within the Glenrosa and Oakleaf soil forms was, therefore, land use.

1.3.1 SOILS OF THE STUDY AREA

Hartmann (1988) states that the predominant group of soils in the Bathurst district are the weakly developed soils interspersed with red sandy clays. The weakly developed members, which dominate this group, have a shallow solum and are typically composed of a dark grey topsoil overlying a subsoil which merges into underlying weathered rock. The remainder of the soils of this group are relatively deep red sandy clays. Both the Glenrosa and Oakleaf soil forms occur in the Bathurst district. The Glenrosa soil form comprises an orthic A horizon overlying a lithocutanic B horizon. The topsoil thus merges into underlying rock. The concept is one of minimal development of an illuvial B horizon in weathered rock. Weathering of rock under a topsoil has produced a heterogenous and highly variegated zone consisting of soil material interspersed with saprolite or weathering rock in various stages of breakdown (MacVicar, 1991).

The Oakleaf soil form, on the other hand, consists of an orthic A horizon overlying a neocutanic B horizon. Neocutanic character is recognized when soil formation in unconsolidated materials has not progressed sufficiently far to produce a distinctive diagnostic horizon, but has brought about reorganization of the material. Soil formation has been minimal and the horizon is marked by rather weak structural development. The presence of cutans indicates pedogenic reorganization of materials such as clay and aggregation of the particles to the extent that the material is no longer single grained (MacVicar, 1991).

1.3.2 CLIMATE OF THE STUDY AREA

According to Schulze (1947), Bathurst falls into the Cfbl climatic type. This climatic type has a subtropical climate with all months displaying a temperature range between 10 and 22.2°C and with at least 60 mm of rain. Box-and-whisker plots display the summary statistics of the various climatic parameters for the period 1977 to 1991 (Figure 1.4). The central box covers the middle 50% of the data values, between the lower and upper quartiles. The 'whiskers' extend out to the extremes (minimum and maximum values), while the central line is at the median. When unusual values occur far away from the bulk of the data, they are plotted as separate points since the whiskers extend only to those points within 1.5 times the interquartile range. The climatic data was supplied by the Department of Agriculture and Water Supply, Dohné for station number 6003, grid reference 33° 31' S and 26° 49' E.

TEMPERATURE

The mean monthly maximum temperature in the Bathurst region ranged from 18.3°C in July to 28°C in January, while the mean monthly minimum temperature ranged from 9.2°C in July to 19°C in February for the period 1977 to 1991 (Figure 1.5a and b). Maximum and minimum temperatures show strong seasonal variations, with the highest values being recorded in January and February and the lowest values being recorded in July.

RAINFALL

According to Köpke (1988), Bathurst falls within the spring maximum rainfall zone. This is illustrated by the higher rainfall figures that occur from August to November (Figure 1.5c).

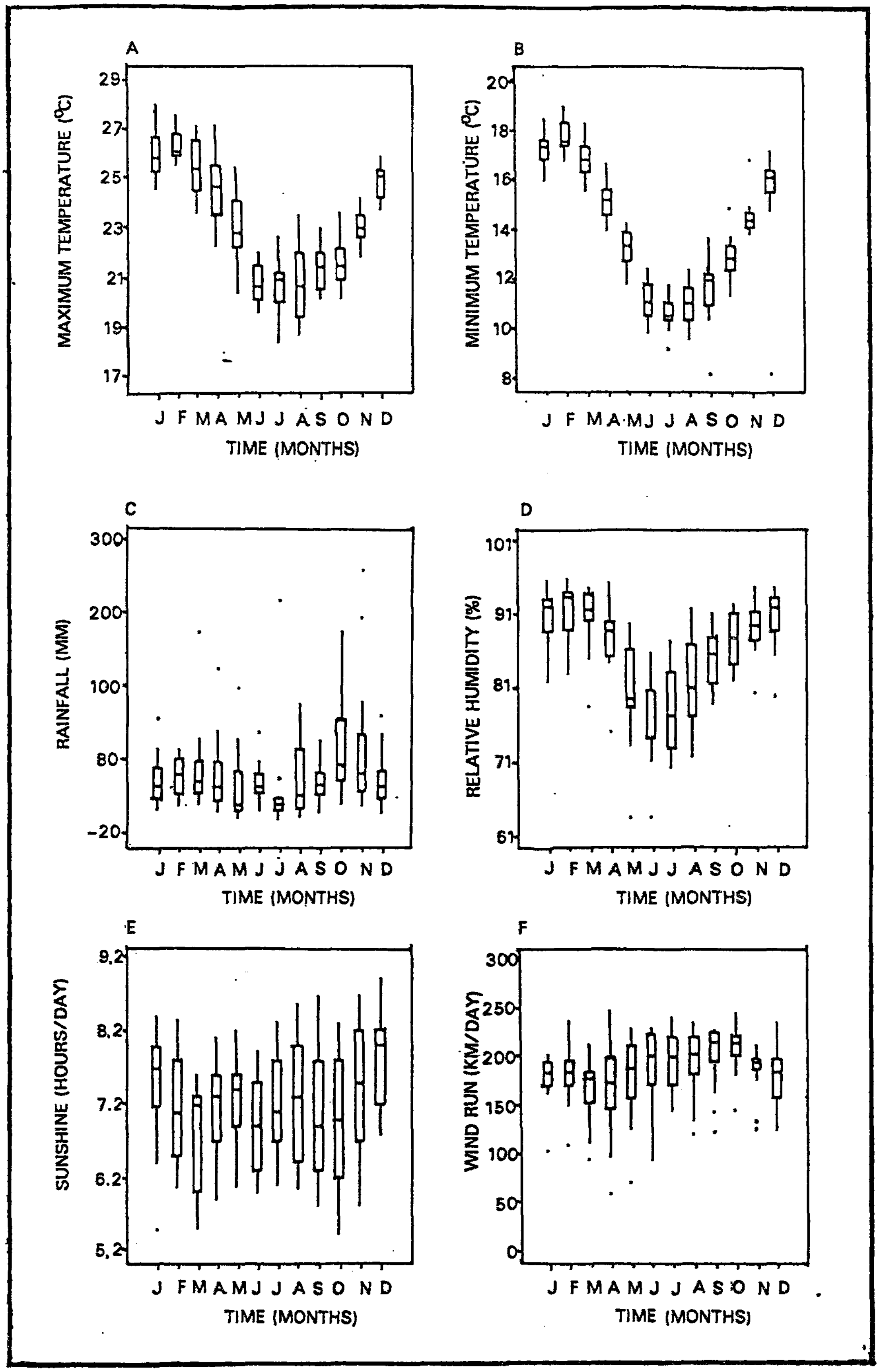


FIGURE 1.5: Climate of Bathurst (1977-1991)

The mean monthly maximum value, 339.7 mm, also fell in the month of November. The mean annual rainfall for the period 1977 to 1991 was 742.9 mm. While a spring maximum rainfall does occur, the eastern Cape is largely a transition zone of climatic types and the seasonality of rainfall is much less pronounced than in other parts of the country (Köpke, 1988).

RELATIVE HUMIDITY

The mean monthly maximum relative humidity ranged from 63.5% in June to 95.5% in April for the period 1977 to 1991 (Figure 1.5d). No strong seasonal variations occurred in the maximum relative humidity data.

SUNSHINE

The mean monthly sunshine ranged from 5.4 $hours.day^{-1}$ in October to 8.9 $hours.\ day^{-1}$ in December between 1977 and 1991 (Figure 1.5e). The average for the period 1977 to 1991 was 7.2 $hours.day^{-1}$. There were more sunshine hours per day during the summer period (November to January).

WIND

Wind run varied from 59.4 $km.day^{-1}$ in April to 246.1 $km.day^{-1}$ also in April (Figure 1.5f). No marked seasonal variations occurred, but wind run was generally higher in the months of June to October.

1.4 THE PILOT STUDY

A pilot study was conducted to investigate the possible effects of pineapple cultivation on factors affecting soil erodibility. Comparisons were made between soil properties in three sites, namely pineapple ridges, pineapple furrows and an undisturbed soil under natural vegetation.

The study area selected was a pineapple land on the Bathurst Agricultural Research Station. The three sites were adjacent to each other, contained the same soil types (Oakleaf, Leeufontein), same slope steepness and slope aspect. The difference between the three sites was, therefore, land use (pineapple cultivation).

On the basis of the theoretical background, a number of factors influencing soil erodibility were selected for investigation, namely bulk density, porosity, organic content, aggregate stability, shear strength and infiltration rate. Ten random samples and measurements were taken separately in the ridges and furrows of the pineapple lands and in the natural vegetation. Samples for the measurement of bulk density, porosity and organic content were collected using the metal ring sampler technique for taking undisturbed samples (Foth et al., 1982). Bulk density was measured in the laboratory using the gravimetric method outlined by Faniran and Areola (1978). Porosity was obtained by expressing the ratio of the bulk density to the particle density as a percentage and subtracting this from 100 (Foth et al., 1982). The particle density of the soils was determined using the pycnometric method (British Standards Institution, 1975). Organic content was measured indirectly by determining the weight loss on ignition (450°C for 12 hours)(Kezdi,1980). Aggregate stability was determined by observing the change in volume (%) of the soil on 30 minute immersion in water (Briggs, 1977). Shear strength was determined using a shear vane as described by the British Standards Institution (1975). Infiltration rate was determined using the infiltrometer ring method described by Young (1980).

The results of the pilot study are shown in Figure 1.6. The Mann-Whitney U Test was used to test the statistical significance of the differences between the data sets (Table 1.1).

TABLE 1.1: Summary of the results of the Mann-Whitney U tests for differences between data sets (Weaver et al., 1991).

Variable	Natural vegetation vs. ridge	Natural vegetation vs. furrow	Ridge vs. furrow
Organic content	*	*	*
Infiltration rate	-	*	-
Shear strength	*	-	*
Bulk density	-	*	*
Porosity	-	-	*
Aggregate stability	-	-	*

*difference significant at the 0.05 level
- difference not significant at the 0.05 level

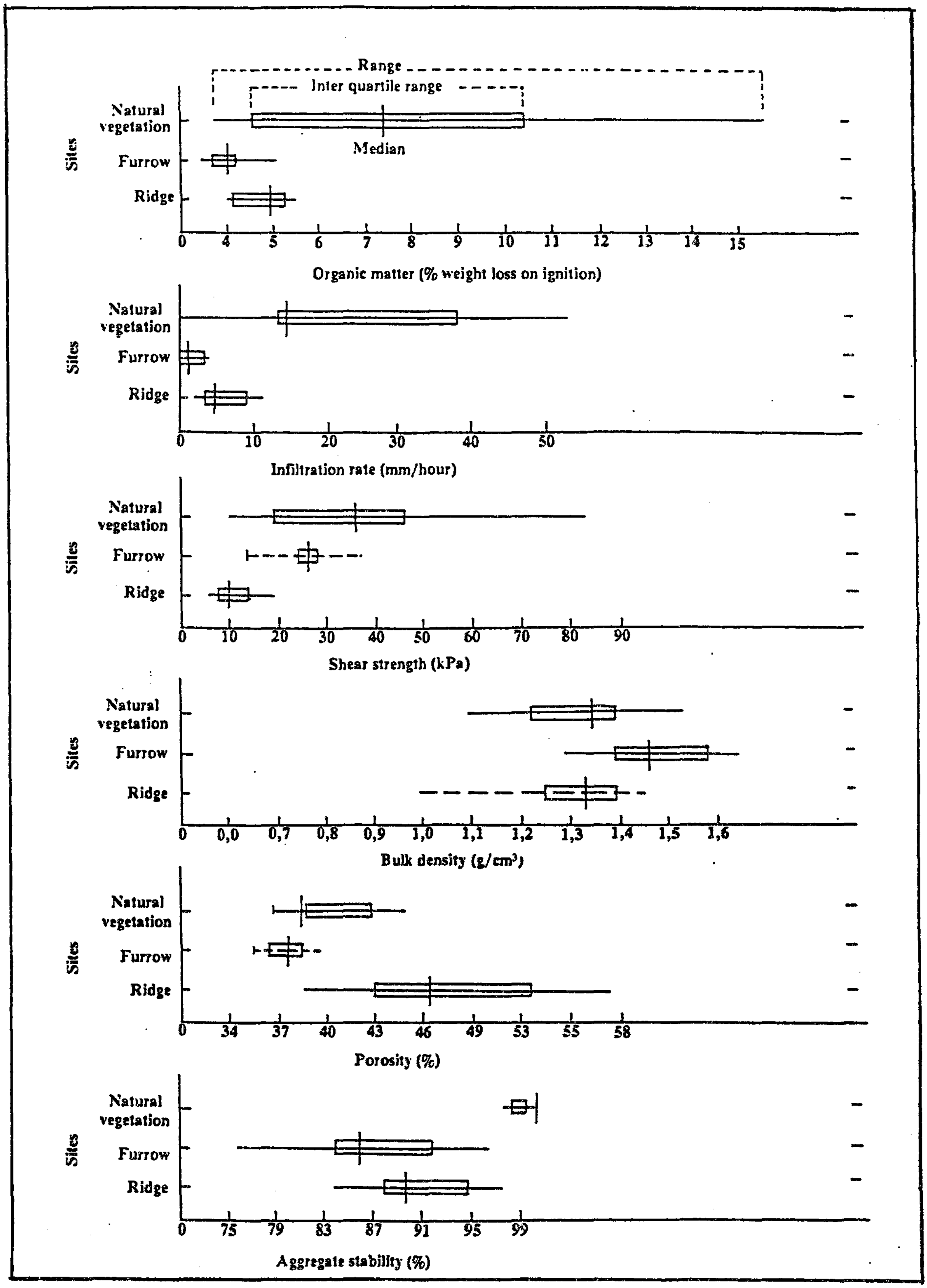


FIGURE 1.6: Block diagrams showing the variations in soil properties for the three sites (Weaver et al., 1991)

The pilot study indicated a number of interesting trends - decreasing organic content, aggregate stability, shear strength and infiltration rate in the soils of the pineapple lands versus those of the natural vegetation - which suggest that pineapple cultivation leads to increased soil erodibility. It must be emphasized that this pilot study was intended to be an initial, exploratory investigation of differences in factors affecting soil erodibility between areas planted to pineapples and adjacent uncultivated land. Based on the pilot study, a more detailed study was recommended. The limited data base (N = 10) allows for tentative conclusion only and emphasizes the fact that further research is essential before definitive conclusions can be drawn. A larger sample size would ensure that the results could be stated with greater confidence. The traffic area adjacent to the pineapple lands was identified as an important area to be included in the study as it this area was perceived to be a major contributor to soil erosion in the pineapple lands. Another recommendation based on the pilot study was that the Walkley-Black method of organic carbon determination be used. The method used to determine organic content in the pilot study (percentage weight loss on ignition) was considered to be inadequate since it is a surrogate method open to criticism due to the possible loss of CO^2 in the heating of carbonates. Investigation into other variables such as soil texture, pH and cation exchange capacity was also seen to be beneficial since it would yield an improved understanding of factors controlling soil erodibility in the pineapple lands.

1.5 THE SIGNIFICANCE OF THE STUDY

There are a number of reasons for the study of soil erodibility. The ultimate aim of all soil erosion and soil erodibility research is to be able to suggest suitable conservation measures (Morgan, 1986). Since the pineapple industry provides a significant source of agricultural income in the Bathurst area, it is vital to conserve the soils under pineapple cultivation in order to sustain their long term productivity. An understanding of the processes and factors that affect soil erodibility in the pineapple lands will aid in improving soil management practices in these areas. Correct soil management may lead to improved soil fertility and structure, resulting in higher crop yields in the pineapple growing regions of Bathurst.

The study of soil erodibility in a spatial context fits well within the discipline of geography considering that Haring and Lounsbury (1983, p.5) define geography as "... the major discipline that is concerned with the identification, analysis and interpretation of spatial distributions as they occur on the surface of the earth." Haring and Lounsbury (1983) continue by stating that all phenomena that occupy space are grist for geographical analysis. Since this thesis investigates differences in factors influencing soil erodibility between four spatial areas, it can be considered within the context of geography. In fact, Faniran and Areola (1978) state that the soil is a typically geographic topic, resulting from and reflecting the interaction of the elements of the earth's surface.

CHAPTER 2

PINEAPPLE CULTIVATION IN THE EASTERN CAPE

Edible pineapples originated in South America and were first introduced to South Africa from Java in 1660 by the Dutch. Pineapples were planted in Natal in 1860 and 1865, Mr C. Purdon was given 35 Natal pineapples tops for experimental planting on his farm in the Bathurst district. By the early 1900's, pineapple production in the eastern Cape was sufficient to meet local demands and in 1907, fresh pineapples were exported to England. The advances made in refrigeration by 1914 allowed increasing quantities and qualities of fruit to be exported. Pineapple fruit was canned for export in 1945 and the export of fresh fruit is now of less importance with over 90 per cent of all fruit produced being exported in the canned form. Domestic fresh fruit markets account for approximately 10 per cent of total pineapple production (Keetch, 1976a).

Today, the South African pineapple industry is the eighth largest producer of pineapples in the world, after Hawaii, Brazil, Malaysia, Taiwan, Mexico, the Philippines and Thailand. In 1980 production exceeded 150 000 tons per annum (Le Grice, 1980).

According to Keetch (1976b), the four main pineapple producing areas of South Africa are:

1. The coastal belt of the eastern Cape including the areas of Kei Mouth, Kidds Beach, East London, Peddie, Bathurst, Salem and Alexandria;
2. The Levubu area of the Northern Transvaal;
3. The Empangeni and Hluhuwe areas of Zululand;
4. The Umkomaas area situated south of Durban.

Five of South Africa's seven pineapple canneries are located in East London, while the other two are at Empangeni and Hluhuwe in Zululand.

In South Africa, a number of different pineapple cultivars are grown, but only the Smooth Cayenne and the Queen are cultivated on a commercial scale. In the eastern Cape, the Smooth Cayenne accounts for over 95% of the local plantings, while along the Natal south coast and in the northern Transvaal, production is confined largely to the Queen (Le Grice, 1980).

Traditionally, the Smooth Cayenne is used by the canning industry, while the Queen is grown for the fresh fruit market.

Due to the distinctive nature of pineapple cultivation, a detailed discussion of the requirements for and the agricultural techniques involved in pineapple cultivation is essential to understand how differences in soil erodibility may arise. This chapter therefore addresses the requirements for pineapple cultivation, the agricultural operations involved in pineapple cultivation and the relationship between pineapple cultivation and soil loss.

2.1 REQUIREMENTS FOR PINEAPPLE CULTIVATION

CLIMATIC REQUIREMENTS

Pineapples are indigenous to the tropics and thrive when grown in areas situated between 25° N and S of the equator (Dalldorf, 1978). However, pineapples are very sensitive to temperature variations and cannot tolerate extremes. For this reason, pineapples are usually grown at low altitudes in close proximity to the coast, where the sea has a moderating effect on the climate.

The major factors influencing the growth of pineapples are temperature, rainfall, humidity, sunshine hours and wind.

TEMPERATURE

Temperature is probably the most important climatic factor influencing the growth of the pineapple plant (Py, Lacoeuilhe and Teisson, 1987). Pineapples grow satisfactorily in a temperature range between 15°C and 30°C, but a temperature of approximately 24°C is necessary for optimal growth. A daily variation between a maximum of 28°C and a minimum of 20°C during the entire growth cycle is considered to be the optimum for plant growth and fruit quality (Le Grice, 1980).

Plant growth is retarded when soil temperatures drop below 20°C and when air temperature drops below 15°C or rises above 30°C. Because temperatures below freezing point cause damage to the plant, pineapples can only be successfully grown in frost-free areas. Air temperatures above 32°C cause a breakdown of the fruit and 'sunburn' results (Dalldorf, 1978).

RAINFALL

The pineapple plant is very adaptable as regards its rainfall requirements, and can produce a crop successfully under a wide range of rainfall conditions. Pineapples can be grown in areas with rainfall that varies from 600 $mm.year^{-1}$, with a dry season lasting several months, to 3500 - 4000 $mm.year^{-1}$ (Py et al., 1987). However, although the pineapple is a drought-resistant plant, an annual summer rainfall of 760 mm is considered necessary. Most of this rain should fall during the warm summer months when growth is most vigorous and evaporation and transpiration are at their maximum. Good rains during the last two months before harvesting are very beneficial and can increase fruit mass considerably. In areas receiving a very high rainfall, it is essential that the soil drainage is excellent, otherwise plants will suffer from various fungal rots and fruit quality may be impaired.

RELATIVE HUMIDITY

All the major pineapple producing areas are in close proximity to large expanses of water which naturally results in a high mean maximum relative humidity (above 75%) (Dalldorf, 1978). A high relative humidity will improve growth in areas with low rainfall, as moisture condenses on the leaves and runs down the centre of the leaf rosette and to the base of the plant.

SUNSHINE HOURS

Plentiful sunshine is necessary for vigorous plant growth and development. Prolonged overcast skies can result in an imbalance of nutrients in the plant, delay fruit development and impair fruit quality. Sideris et al. (1936) were the first to demonstrate the influence of sunlight on yield. With 33, 50, 60, and 100% light intensity in Wahiawa, Hawaii from 10 months after planting on, fruit weight was 60, 71, 74 and 100% respectively. According to Sanford (1962), each 20% reduction in sunlight reduces yield by 10%. Sunlight is therefore an indispensable factor in plant nutrition.

WIND

The pineapple plant is fairly resistant to wind damage, but Nightingale (1942) observed that wind over a prolonged period, even if moderate, can reduce the size of the plant by 25%. Strong cold winds do cause severe mechanical damage to the leaves, after which *Thielaviopsis* infection may take place, causing 'white leaf spot'. Wind may also blow newly planted material out of the ground, and fill the hearts of small plants with soil thereby increasing the risk of 'heart rot', caused by soil-borne fungi (*Phytophthora* spp.)

SOIL REQUIREMENTS

The primary soil requirement of the pineapple plant is good drainage and provided that this condition is met, pineapples can be grown on a variety of soil types. Great care must therefore be taken in laying out a pineapple plantation to ensure good drainage and the removal of surplus water. The plant prefers an acid soil, and therefore in soils of pH greater than 6, yields are adversely affected. Since the plant has a relatively shallow rooting system, soil depths in excess of 45 cm are unnecessary (Langenegger and Dalldorf, 1978).

2.2 FARMING OPERATIONS INVOLVED IN PINEAPPLE CULTIVATION

Soil preparation commences with the clearing of virgin natural vegetation if available and, if not, the clearing of old pineapple plantations. An old plantation may be burned and then knocked down with heavy discs - or cut down by means of a bush-slasher. The soil is disced, ploughed and tilled a number of times to achieve as fine a tilth as possible. While this is essential for effective plant rooting, destruction of grass roots and effective soil fumigation and weed control, tillage is known to break down soil structure, reducing the stability of peds.

In the past, pineapples have been grown on flat, unridged soil. However, it has been shown that ridges, even on sloping ground, result in better plant growth and yields. The reasons include improved drainage, better soil moisture and temperature retention and improved aeration for the roots. The accepted practice is therefore to cultivate pineapples on ridges which are approximately 600 mm wide with a canal about 250 mm wide by 200 mm deep on each side (Figure 2.1) (Kieck and Denyer, 1986).

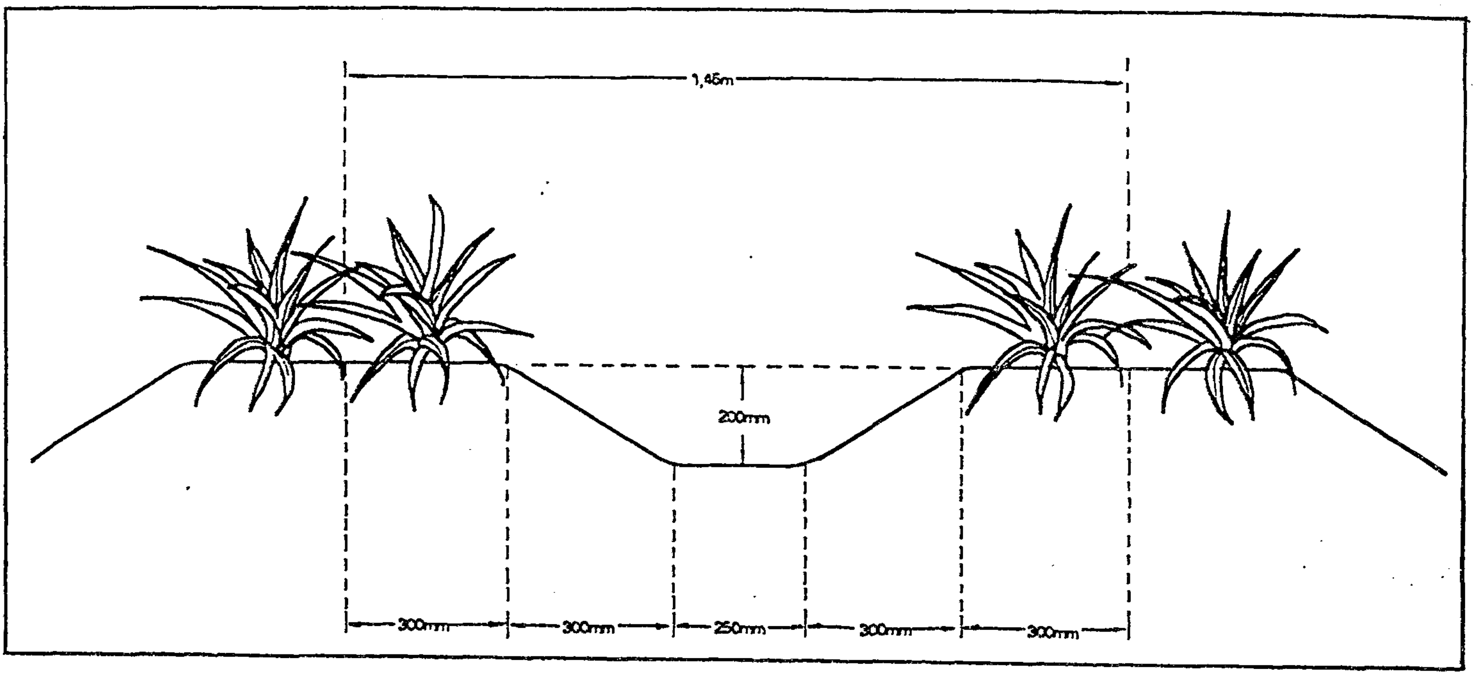


FIGURE 2.1: Cross section of ridges

However, by adopting the ridging approach to pineapple cultivation, the following problems are experienced:

1. The ridges have microslopes which are exposed to raindrop action and runoff erosion for up to 2 years before canopy cover protects these microslopes.
2. The cultivation practice of ridging results in the concentration of runoff water in the furrows. The general practice of ridging up and down the slope leads to greatly increased flow velocity, and as a result, scouring in the furrows becomes excessive.

Planing the layout and providing for runoff control from pineapple lands differs considerably from the systems adopted with other crops. Kieck and Denyer (1986) give four basic reasons for this:

1. The cultivation and harvesting of pineapples is largely mechanical and utilises a boom spray for the application of fertilisers and herbicides and a boom harvester for harvesting. A system is therefore needed whereby it is possible to drive the tractor operating the boom spray along roadways which are spaced so as to ensure that the entire land is covered by spray, but that overspraying is avoided.

2. In order to facilitate drainage, pineapples are cultivated on steep slopes of up to 20% and often on fairly highly to highly erodible soils.
3. The accepted practice is to cultivate pineapples on ridges up and down slopes.
4. Pineapple lands are kept clear of all other vegetation for up to 3 years. Since the plant itself provides virtually no cover for the first 18 months, it can only be considered as providing reasonable resistance to raindrop action from the age of 2 years.

The layout of the pineapple lands in block systems thus encourages surface runoff as opposed to infiltration of rainfall. The use of a surface mulch (plok), the contour system layout and correctly positioned waterways can, however, reduce the amount and velocity of runoff in the pineapple lands.

In the eastern Cape, planting occurs throughout the year, with the exception of the months of March and April when the air temperatures are too high and the soil is too dry (Hill, 1991). Spring (September to December in the Eastern Cape) is generally regarded as the most optimum period for planting when the moisture and temperature conditions are ideal. However, much of the rain which falls during this season is convective rainfall which is highly erosive. Since the soil is exposed as a consequence of planting, convective rainfall during this period may result in high rates of soil loss. Most growers are concerned with harvesting the winter fruit from June to October and the summer fruit from February to May, leaving October to January for planting.

Fertiliser is applied by hand to the plants approximately 6 weeks after planting. When the plants have achieved sufficient leaf area, monthly fertiliser sprays are given. Most growers use a boom spray unit for this purpose. The fertilisers sprayed onto the pineapple plants contain nitrogen, potassium, iron and zinc. About 12 sprays are given from planting to the time of flower induction for the first crop. Large supplies of fertiliser (particularly nitrogen and potassium) may, however, result in acidification and depletion of soils (Py et al., 1987).

Harvesting is a labour intensive process. Most of the large pineapple growers have boom harvesters. These harvesters have conyevor belt systems which take the fruit from within a block and deposit it in bulk bins on trailers in front of or behind the harvester. The conveyor boom, which covers half a block, is usually mounted on a tractor. The labourers walk in the furrows behind the boom, pick the pineapples and deposit them onto the conveyor belt. Both the road and furrow areas are thus exposed to considerable vehicular and foot traffic. The tractor-drawn trailers are taken to central loading depot where the bulk bins are placed on a road transporter which takes fruit to the cannery. As the fruit is picked, the tops are taken off and left in the land to be collected for planting at a later stage.

It is approximately a time period of six years from the initial soil preparation and ridging to the harvesting of the third crop (second ratoon) (Table 2.1).

TABLE 2.1: Summary of the operations involved in pineapple production (Le Grice, 1980).

YEAR AND MONTH			FARMING OPERATIONS
YEAR 1	1	July	*Ridging-Fumigate-Preplant Fertiliser-Planting-Weedkiller
	2	August	Ridging-Fumigate-Preplant Fertiliser-Planting-Weedkiller
	3	September	Ridging-Fumigate-Preplant Fertiliser-Planting-Weedkiller
	4	October	Ridging-Fumigate-Preplant Fertiliser-Planting-Weedkiller
	5	November	Plant Crop Fertiliser Hand Dressing
	6	December	Plant Crop Fertiliser Spray
	7	January	Plant Crop Fertiliser Spray
	8	February	Fertiliser Hand Dressing
	9	March	Plant Crop Fertiliser Spray
	10	April	Plant Crop Fertiliser Spray
	11	May	Plant Crop Fertiliser Spray
	12	June	Plant Crop Fertiliser Spray
YEAR 2	13	July	Plant Crop Fertiliser Spray
	14	August	Plant Crop Fertiliser Spray
	15	September	Plant Crop Fertiliser Spray
	16	October	Plant Crop Fertiliser Spray
	17	November	
	18	December	Artificial forcing of Plant Crop using Ethrel
	19	January	Fruit Development
	20	February	Fruit Development
	21	March	Fruit Development
	22	April	Spray Pineapple Frutone CPA sizing agent
	23	May	Fruit Development
	24	June	Fruit Development
YEAR 3	25	July	Ethrel Ripening Spray
	26	August	Harvest Plant Crop
	27	September	First Ratoon Fertiliser Spray
	28	October	First Ratoon Fertiliser Spray
	29	November	First Ratoon Fertiliser Spray
	30	December	First Ratoon Fertiliser Spray
	31	January	First Ratoon Fertiliser Spray
	32	February	First Ratoon Fertiliser Spray
	33	March	First Ratoon Fertiliser Spray
	34	April	
	35	May	Force First Ratoon Suckers using Ethrel
	36	June	Fruit Development
YEAR 4	37	July	Fruit Development
	38	August	Fruit Development
	39	September	Fruit Development
	40	October	Spray Pineapple Frutone CPA sizing agent
	41	November	Fruit Development
	42	December	Fruit Development
	43	January	Ethrel ripening spray
	44	February	Harvest First Ratoon Crop
	45	March	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
	46	April	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
	47	May	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
	48	June	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
YEAR 5	49	July	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
	50	August	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
	51	September	2nd Ratoon Fert. Spray OR Knock down and Soil Prep.
	52	October	
	53	November	Force 2nd Ratoon Suckers using Ethrel OR Ridge-Fumigate-Fert-Plant-Weed
	54	December	Fruit Development OR Ridge-Fumigate-Fert-Plant-Weed
	55	January	Fruit Development OR Ridge-Fumigate-Fert-Plant-Weed
	56	February	Fruit Development OR Carry on as for Plant Crop Above
	57	March	Fruit Development
	58	April	Spray Pineapple Frutone CPA sizing agent
	59	May	Fruit Development
	60	June	Fruit Development
YEAR 6	61	July	Ethrel Ripening Spray
	62	August	Harvest Second Ratoon Crop
	63	September	Knock Down and Soil Preparation
	64	October	Knock Down and Soil Preparation
	65	November	Knock Down and Soil Preparation
	66	December	Knock Down and Soil Preparation
	67	January	Knock Down and Soil Preparation

The cultivation history of the Glenrosa and Oakleaf soil forms records exactly when each agricultural process was carried out in the pineapple lands (Table 2.2).

TABLE 2.2: The cultivation history of the Glenrosa and Oakleaf soil forms (Purdon, 1991).

GLENROSA SOIL FORM HISTORY	
JUNE 1986	Cleared natural vegetation
	Soil preparation
	Ridged soil
	Fumigated soil
	Applied preplant fertilizer
	Applied weedkiller
	Planted pineapples
DECEMBER 1987	Plant crop artificially forced
SEPTEMBER 1988	Plant crop harvested
NOVEMBER 1988-APRIL 1989	Applied fertilizer
MAY 1989	First ratoon artificially forced
APRIL 1990	First ratoon harvested
OCTOBER 1990	Applied fertilizer
APRIL 1991	Second ratoon artificially forced
MARCH 1992	Second ratoon will be harvested

TABLE 2.2 continued: The cultivation history of the Glenrosa and Oakleaf soil forms (Purdon, 1991)

OAKLEAF SOIL FORM	
NOVEMBER 1988	Cleared natural vegetation Soil preparation Ridged soil Fumigated soil Applied preplant fertilizer Applied weedkiller Planted pineapples
JUNE 1990	Plant crop artificially forced
MAY 1991	Plant crop harvested
MAY 1991 - JANUARY 1992	Applied fertilizer
FEBRUARY 1992	First ratoon will be artificially forced

2.3 PINEAPPLE CULTIVATION AND SOIL LOSS

Denyer (1984) posed the question: "Is the pineapple industry an erosion hazard?". Preliminary results from rainfall simulator tests undertaken in the Albany and Bathurst districts indicate soil losses which vary between 2.5 and 73 $t.ha^{-1}$ following 60 minute, 63 $mm.hr^{-1}$ storms on ridged soil (Denyer, 1984) (Figure 2.2). Kieck (1984) also showed quite clearly that the ridging process aggravates the erosion taking place and increases the soil loss process threefold (Table 2.3).

TABLE 2.3: Soil loss - Normal flat tillage compared with ridged soil for new pineapple plantings (Kieck, 1984).

Soil form	Slope	Reference	Ridged	Ratio Ridged vs Ref.
Mayo	3–8%	0,8t/ha	2,5t/ha	3 x more soil loss with ridges
Glen Rosa	3–11%	10,5t/ha	25,2t/ha	2,5 x more soil loss with ridges
Kroonstad	4–5%	8,5t/ha	27,0t/ha	3,2 x more soil loss with ridges
Longlands	7–9%	23,2t/ha	74,0t/ha	3,2 x more soil loss with ridges

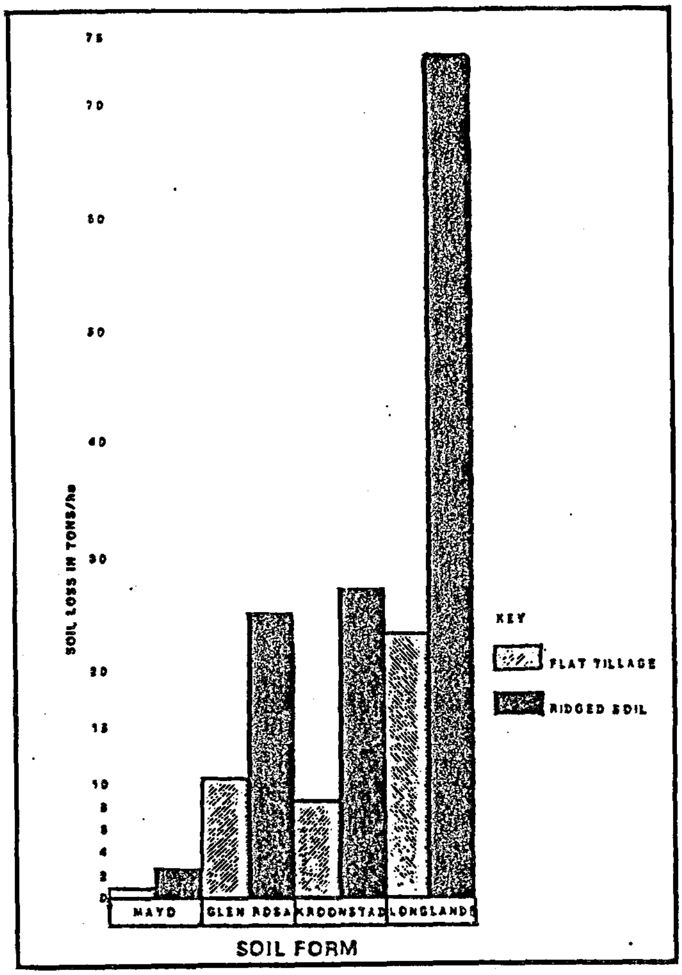


FIGURE 2.2: Comparison of soil losses resulting from a single 60 minute, 63 $mm.hr^{-1}$ storm on ridged soils and on flat tillage areas (Denyer, 1984).

Pineapple farmers are, therefore, by their cultivation practices, accelerating soil erosion. Factors which contribute to high soil losses from pineapple lands include ridging the soil (which increases yields) and ploughing large expanses of land which are too steep or highly erodible. Roose and Asseline (1978) quoted in Py et al. (1987) state that the erosion risk on pineapple lands can be considered particularly high on slopes of more than 2 to 3%. Also, during the process of soil preparation, the soil is mechanically worked to a fine tilth, making it susceptible to erosion. Another factor which contributes to the erosion risk on pineapple lands is that the lands are laid out on block systems. This is done to accommodate the highly mechanized production techniques. However, in many cases these block systems ignore the principles of water runoff control since the blocks are laid up and down the slope. Yet another factor increasing the erosion risk in pineapple lands is that the lands are kept clear another factor increasing the erosion risk in pineapple lands is that the lands are kept clear of all other vegetation. Since pineapples grow slowly, the soil is exposed (especially during the early months) to raindrop impact (Py et al., 1987).

Results from rainfall simulation studies have shown that judicious mulching using residue from previous pineapple crops (plok) can reduce the soil loss by 30-fold when used in conjunction with minimum tillage practices (Kieck, 1984). Field trials on a Glenrosa soil form with a slope of 13% and ridges 18 m long, indicated that furrows with no plok application lost 26.4 and 30.3 $t.ha^{-1}$ as opposed to furrows treated with 12 and 22 tons of plok respectively from which there was no measurable soil loss (Figure 2.3) (Department of Agriculture and Water Supply, 1989).

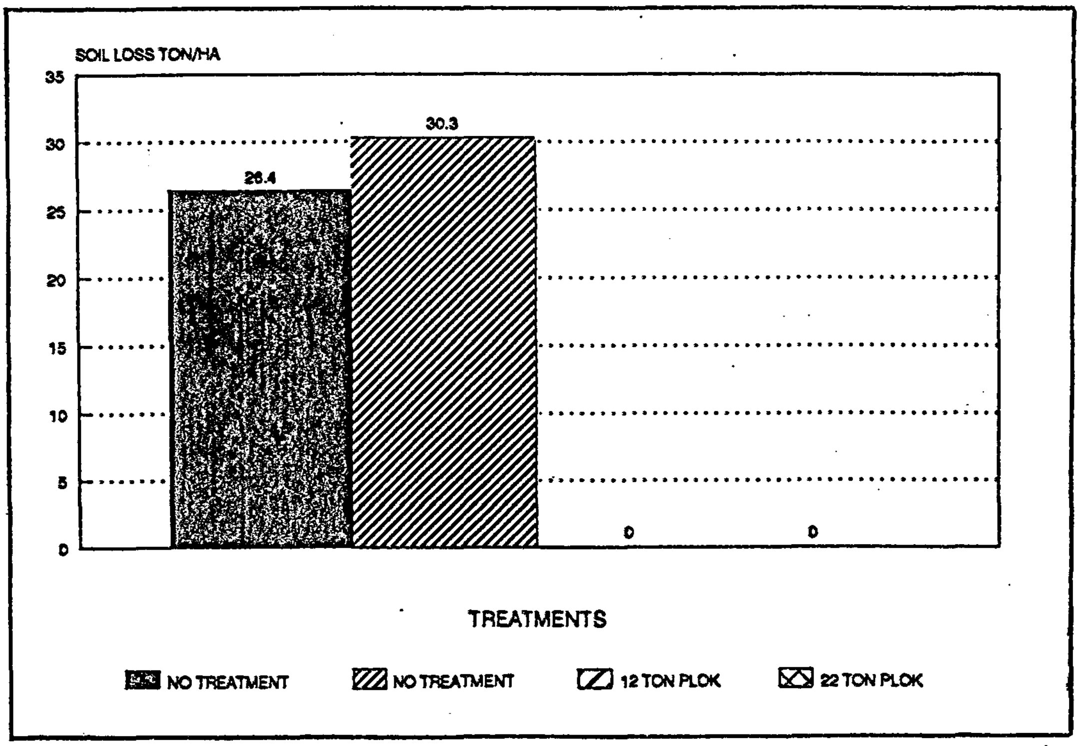


FIGURE 2.3: Soil losses on Glenrosa soil with a 13% slope (Department of Agriculture and Water Supply, 1989)

It thus appears from the literature that the agricultural operations involved in pineapple cultivation accelerate soil erosion. A possible solution to this problem is the application of

CHAPTER 3

FACTORS INFLUENCING SOIL ERODIBILITY

While it is generally understood that the dominant factors controlling the severity of soil erosion are rainfall, topography and vegetation cover, it is also recognised that even when these factors remain constant, differences in soil properties may cause differences in soil loss (Bryan, 1968). Zachar (1982) states that each soil type has a certain ability to withstand erosion, displaying an erodibility which is closely related to specific soil properties. Morgan (1986) defines erodibility as the resistance of the soil to both detachment and transport and states that the properties of the soil are the most important determinants of soil erosion, although soil resistance also depends partly on topographic position, slope steepness and interference by man. Soil erodibility is therefore an inherent property of a soil which reflects the fact that different soils erode at different rates when all other factors controlling erosion are the same (Mitchell and Bubenzer, 1980).

Man's activities may, however, change the erodibility of soils as a consequence of land use and management changes. The increasing pressure on agricultural land may also necessitate the cultivation of potentially marginal land of high soil erodibility. It is therefore vitally important to monitor changes in soil erodibility and develop methods which accurately predict erodibility so that agricultural practices can be designed to conserve the soil.

The current chapter presents a review of the available literature on the development of soil erodibility theory, the factors controlling erodibility and the impact of cultivation on the factors controlling soil erodibility.

3.1 DEVELOPMENT OF SOIL ERODIBILITY THEORY

Soil erodibility can be assessed by direct observation of soil loss under controlled conditions or by the isolation of various soil properties or indices of erodibility. To directly measure soil loss is extremely time consuming and often requires expensive and elaborate equipment. However, indices of erodibility can usually be derived from normal analytical data, do not require expensive equipment and can be measured quickly for a large number of soils

(Elwell,1986). The merits of isolating soil properties to act as indices of erosional response are therefore apparent. It must, however, be emphasized that there is no single index or factor that measures soil erodibility.

Many attempts have been made to determine which factors influence soil erodibility and to devise a simple index or method of measurement for erodibility. Research into the quantification of soil erodibility was initiated by Duley and Miller in 1923. Duley and Miller demonstrated that under certain conditions, soil properties exert strong control on the severity of surface erosion. Bennett's (1926) pioneer work on the erodibility of Cuban latosols did not attempt to establish an index of erodibility, but indicated a number of significant properties influencing soil erodibility; namely texture, structure, organic matter and chemical composition. Bennett also found a direct relationship between erosion and the ratio of SiO_2/R_2O_3. Middleton (1930) was the first researcher to identify a number of factors that determine the erodibility of a soil. These included the mechanical structure, colloid content, moisture content, soil density, capillary water balance, plasticity, soil swelling capacity, soil shrinkage and the dispersion ratio. The dispersion ratio is calculated by comparing the amount of silt and clay in an undispersed sample with that in a sample previously treated with a dispersing agent. Middleton also discovered that the 'erodible' and 'non-erodible' soils which he examined differed significantly in the ratio of colloid content to moisture equivalent. Middleton considered that this ratio could be used as an indirect measure of the soils water-holding capacity, and, therefore as a direct index of its ability to transmit water. Since erosion is caused by runoff, and the quantity of runoff is closely related to the ability of soil to transmit moisture, the 'colloid content/moisture equivalent' ratio may be used as an indirect index of erodibility. Middleton then combined the 'colloid content/moisture equivalent' ratio with the dispersion ratio to provide a further direct measure of erodibility which he termed the 'erosion ratio', and which he considered to be the most accurate index of erodibility:

$$\text{Erosion ratio} = \frac{\text{Dispersion ratio and Moisture equivalent}}{\text{Colloid content}} \qquad \text{(E3.1)}$$

For this ratio a value of 10 was considered to be a threshold between 'erodible' and 'non-erodible' soils. According to Middleton, "... a soil which is resistant to erosion has a larger content of clay particles, a higher colloid content to equivalent moisture ratio, a greater specific weight with respect to the soil phase of the soil, a lower plastic limit, a lower dust content, a smaller dispersion and erosion ratio..." (Zachar, 1982, p. 165).

Following an assessment of the validity and efficiency (determined by measuring how closely changes in soil loss under simulated rainfall were reflected by changes in the indices) of various indices of erodibility, Bryan (1968) states that the dispersion ratio is unsatisfactory since it makes no allowance for the ability of high velocity raindrops to disperse undispersed material. The reliance of this technique on the measure of clay and silt content, is also considered problematic, particularly for soils with a high sand content. Bryan (1968) also suggests that as colloid content and moisture equivalent are measures of closely related soil properties, it is not correct that their ratio should be an index of water transmission status. Middleton also places a limit of 10 for the erosion ratio of erodible and non-erodible soils. Since all soils are erodible to some degree, it is incorrect to place an absolute value on erodibility. An index of erodibility can only measure relative erodibility.

Lutz (1934) suggested that there was a strong relationship between erodibility and the state of aggregation. Lutz examined Davidson and Iredell soils from North Carolina and found that the soils differed in aggregation characteristics. The aggregates of the erodible Iredell were small, dense and impermeable, while those of the 'non-erodible' Davidson were large and porous.

Bouyoucos (1935) proposed the 'clay ratio' as a direct index of erodibility, that is, the ratio of the clay content to the sand plus silt content:

$$E = \frac{\%\ \text{Sand} + \%\ \text{Silt}}{\%\ \text{Clay}} \quad \text{(E3.2)}$$

This is essentially a measure of the proportions of binding material. The 'clay ratio' has the advantage of being founded on fundamental principles and only requires basic textural analysis (Bryan, 1968). However, Bryan (1968) states that the 'clay ratio' overemphasizes the importance of clay as a binder and ignores the influence of organic material which may be a more important cementing agent. Another criticism of this index is that when the clay content of the soil drops below 10%, the ratio may become meaningless due to the high water transmission status.

Together with physical and chemical methods, other methods were developed which relied on an analysis of the physical structure of the soil. The use of an indicator of soil resistance was studied by a number of workers; the most comprehensive study was carried out by Vilenskii (1935) who based his work on the theory that structure is the most important property of cultivated soils. Vilenskii proposed that the quantity and quality of aggregates determine both the infiltration rate of water into the soil and the resistance of the upper soil layers to soil splash and soil wash. Vilenskii's method comprises direct testing of the erosion resistance of undisturbed soil aggregates. Vilenskii based the determination of the soils resistance to erosion on the following measurements:

1. The structural content of dry soil using sieves with 0.25 to 15mm meshes
2. The density and porosity of aggregates
3. Rate of water uptake by aggregates after preliminary capillary saturation and by dry aggregates in a crystallizer
4. Rate of water uptake by aggregates during their bombardment by two drops per second from 5 cm height. The resistance of the aggregates is expressed in terms of the amount of water required to saturate the aggregate.
5. Intensity of surface wash in a cylindrical sample of soil collected with minimum disturbance of the structure, and at different moisture levels. Samples were exposed to artificial sprinkling with an intensity of 1 $l.minute^{-1}$ for 15 minutes. The wash intensity was assessed by the amount of washed earth collected.

While this method is considered to be a reliable method, a weakness of the soil aggregation method is that it is dependant on an attribute which is very unstable, both in the field and in the laboratory and is greatly influenced by the moisture content of the sample (Zachar, 1982).

According to Morgan (1986), Middleton's (1930) research was continued in the Soviet Union by Voznesensky and Artsruni (1940) who concluded that the best predictor of erodibility includes properties of aggregatedness, dispersivity and hydrophily or water-retaining capacity according to the formula:

$$\text{Erosion index} = \frac{d\,h}{a} \quad \text{(E3.3)}$$

where d is an index of dispersion
(ratio of % particles > 0.05 mm without dispersion to % particles <0.05 mm after dispersion of soil by sodium chloride)

h is an index of water retaining capacity
(water retention of soil relative to that of 1 g of colloids)

a is an index of aggregation
(% aggregates > 0.25 mm after subjecting the soil to a water flow of 100 cm/minute for 1 hour)

Bryan (1968) considers Voznesensky and Artsruni (1940) method to be soundly based as it involves measurement of all the properties governing the soils resistance to erosion.

Anderson (1954) developed an index of erodibility which was an extension of Bouyoucos' (1935) 'clay ratio' classification. The 'surface aggregation ratio' was the ratio between the total surface area of particles larger than 0.05 mm in diameter and the quantity of aggregated silt and clay. Anderson (1954) found the surface aggregation ratio to correlate highly with suspended sediment discharge in 33 watersheds in Oregon. In 1961, André and Anderson extended the surface aggregation ratio in an investigation of the effect of geology, geographic zones, elevation and vegetation on soil erodibility in the Northern Californian wildlands:

$$\text{Surface aggregation ratio} = \frac{\text{Surface area of particles} \geq 0.05\text{ mm}}{\%\text{ Silt} + \%\text{ Clay in dispersed soil} - \%\text{ Silt} = \%\text{ Clay in undispersed soil}} \quad \text{(E3.4)}$$

The surface aggregation ratio was compared to Middleton's (1930) dispersion ratio and was discovered to be a slightly more efficient index.

Woodburn and Kozachyn (1956) used aggregate stability and the dispersion ratio as indices of erodibility of soils in 23 Mississippi watersheds. Both indices were compared with artificially simulated rain splash losses as a direct measure of erosion. Soil losses by laboratory splash generally compared very well with results by the aggregate stability method (a good inverse relationship occurred between percentage weight water stable aggregates > 0.5 mm diameter and splash loss), but comparative research under natural rainfall produced inconsistent results.

Hénin, Monnier and Combeau (1958) approached the challenge to devise an index of erodibility by using an instability index:

$$\text{Instability index} = \frac{\%\ \text{Silt} + \%\ \text{Clay}}{\text{Ag air} + \text{Ag alc} + \text{Ag benz}} \qquad \text{(E3.5)}$$

where Ag is the % aggregates >0.2 mm after wet sieving for no pretreatment and pretreatment of the soil by alcohol and benzene respectively.

This index was later modified by Combeau and Monnier (1961):

$$\text{Instability index} = \frac{\%\ \text{Silt} + \%\ \text{Clay}}{\%\ \text{aggregates} > 0.2\ \text{mm after wet sieving} - 0.9\ (\%\ \text{coarse sand})} \qquad \text{(E3.6)}$$

Chorley (1959) in attempting to explain the geomorphic significance of soils in the vicinity of Oxford (England), studied the physical properties of soils over a range of parent materials. The properties examined were moisture content, soil density, grain size, range of grain size, permeability and shearing resistance. Chorley thus produced an index of resistance:

$$\text{Resistance} = \frac{\text{Soil density} \times \text{Range of sand grain size}}{\text{Soil moisture content}} \qquad \text{(E3.7)}$$

The mean shearing resistance was then combined with a figure for permeability to obtain an index of erodibility:

$$\text{Resistance} = \frac{1}{\text{Mean shearing resistance} \times \text{permeability}} \qquad \text{(E3.8)}$$

Bryan (1968) criticises Chorley's index by stating that while shearing resistance is very important with regard to mass movement, it is not a prevailing factor affecting soil erodibility. Bryan (1977) also criticised Chorley's study since a penetrometer was used and not a shear vane. This is a problem, since the relationship between penetrability is neither simple nor direct. Another problem results from the fact that the penetrometer measurement is normal to the surface while stress generated by running water acts parallel to the surface. Bryan (1977), however, does state that for non-agricultural purposes, for example hillslope geomorphology, an erodibility index based on a direct measurement of shear strength would be preferable.

Bryan (1968) reviewed 30 years of literature on the development and use of soil erodibility indices. The efficiency of indices of erodibility was determined by measuring how closely changes in soil loss under simulated rainfall were reflected by changes in the various indices. The most efficient indices of soil erodibility were found to be percentage weight if water stable aggregates (W.S.A.) > 3 mm, percentage weight W.S.A. > 0.05 mm, erosion ratio, surface aggregation ratio and clay ratio. A further study by Bryan (1977) proposes that amongst the indices currently available, the W.S.A. methods, particularly W.S.A. > 0.05 mm appear to be the most useful and have the advantage of being simple to apply.

Bruce-Okine and Lal (1975), researching 2 tropical soils in Western Nigeria, characterised soil erodibility using a raindrop technique. This was compared to soil behaviour towards erosion under natural conditions. The water drop test calculated the % aggregates destroyed by a preselected number of impacts by a standard raindrop (for example, 5.5 mm diameter, 0.1 g from a height of 1 m). Aggregate size, initial soil moisture potential and raindrop temperature were tested for their effect on the structural stability of soils. High moisture potential significantly increased the erodibility of a clayey soil containing lattice clay minerals, but slightly decreased the erodibility of a sandy clay loam soil. An increase in water temperature increased the erodibility of both soils. Erodibility was found to vary directly with sand and indirectly with clay content.

Morgan (1986) states that soil erodibility has been satisfactorily described by the Universal Soil Loss Equation's (USLE) erodibility index (K) of Wischmeier, Johnson and Cross (1971).

The K value can be defined as the soil loss per unit of EI30 (a rainfall erosivity compound of kinetic energy and the maximum 30-minute rainfall intensity) as measured in the field on a standard bare soil plot, 22 m long and of 5° slope. Using rainfall simulators on 55 soil types in the fallow condition, five soil erodibility parameters were isolated to be included in the soil erodibility nomograph. The factors included were percentage silt plus very fine sand, percentage sand greater than 0.10 mm, organic content, structure and permeability (Figure 3.1).

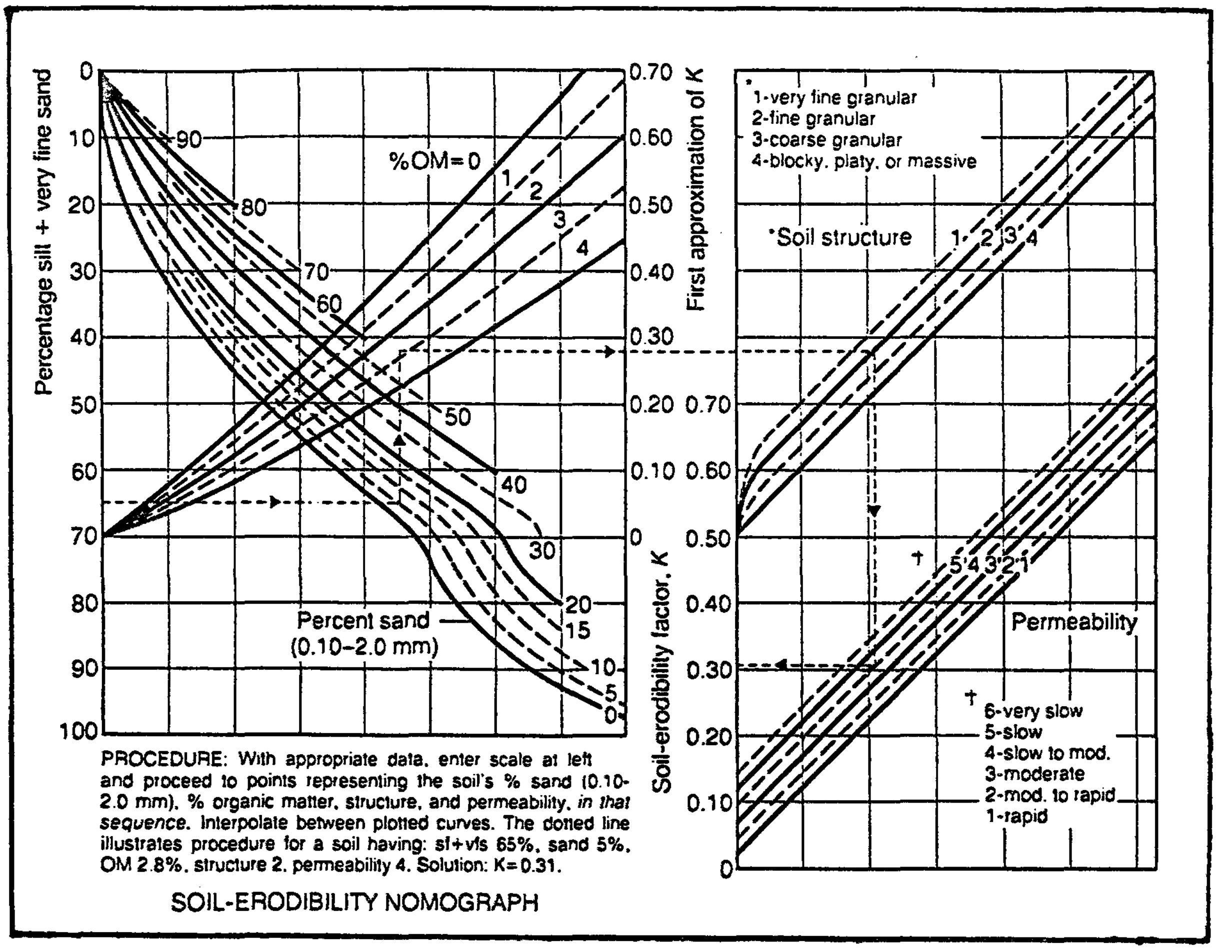


FIGURE 3.1: Nomograph for computing the K value of soil erodibility for use in the Universal Soil Loss Equation (Wischmeier, Johnson and Cross, 1971).

Where the K values have been determined from field measurements of erosion, Morgan (1986) considers them to be valid. However, difficulties sometimes arise when attempts are made to predict soil erodibility from the nomograph of Wischmeier, Johnson and Cross

(1971). Where the nomograph is applied to soils with similar characteristics to those on which the nomograph was derived, a close correlation occurs between predicted and measured values. Ambar and Wiersum (1980), while investigating erodibility indices in West Java, Indonesia, concluded that the K value was the most reliable index available. However, Vanelslande et al. (1984) found little correlation between K-nomograph values and plot-derived erodibility indices in Nigeria. The nomograph also gives poor predictions of soil erodibility on soils which have organic contents of above 4%, swelling clays (Morgan, 1986), high exchangeable sodium percentage (D'Huyvetter and Laker, 1985) and those where resistance to erosion is a function of aggregate stability rather than primary particle size (Schieber, 1983).

Although the USLE is a simple management tool, it does have a number of limitations. The major criticism of the USLE is that it is a method in which empirical relations are combined in equations to predict average soil loss from fields with specific combinations of land use and management. It does not satisfy the need for a detailed model that simulates soil erosion or erodibility as a dynamic process, nor does it describe soil movement along a slope (Mitchell and Bubenzer, 1980). However, the RUSLE (Revised Universal Soil Loss Equation) is the result of the current project to update the USLE. The changes include the development of a seasonally variable soil erodibility term (K). Experimental data show that the K values are not constant but vary with season, being highest in spring from freeze-thaw actions and lowest in mid-autumn and winter following rainfall compaction or a frozen soil. The seasonal variability is addressed by weighting the instantaneous estimate of K in proportion to the EI (the percentage of annual rainfall erosivity factor) for 15-day intervals. Instantaneous estimates of K are made from equations relating K to the frost-free period and the annual rainfall erosivity factor. An additional change incorporated in the RUSLE is to account for rock fragments on and in the soil. K is adjusted for rock in the soil profile to account for rock effects on permeability and, in turn, runoff (Renard et al., 1991).

The only existing index of erodibility which has been widely used in southern Africa is the F index as advocated by the Soil Loss Estimator for Southern Africa (SLEMSA, 1976). The basic index is derived from textural analysis of the soil. Adjustments to the basic index are made according to various criteria, such as surface crusting, tillage practice and to layers of low permeability. Hartmann, McPhee and Bode (1987) investigated 5 morphologically dissimilar soil forms in the East London district of South Africa, and found a reasonable correlation between the F index and the K factor. Hartmann, McPhee and Bode (1989) then investigated the erodibility of various soil series in the pineapple-producing coastal area of the Eastern Cape and found that the measured soil losses were only weakly correlated (r = -0.42) with the basic indices of SLEMSA, and unrelated (r = -0.23) to the K values determined from the nomograph of Wischmeier, Johnson and Cross (1971). A possible reason for these findings is that sodic subsoils occurring in the study area could lead to severe erosion, even though the topsoil may not be erodible *per se*. The applicability of the F index and K value under eastern Cape is thus uncertain.

A point which should be emphasized is that soil erodibility is a dynamic rather than a static characteristic. None of the indices reviewed either allow for or have been related to seasonally varying soil conditions in any comprehensive manner (with the possible exception of the proposed RUSLE). Pall et al. (1982) attempted to identify soil characteristics which could explain much of the temporal (seasonal) variation in soil erodibility. Although the data base was acknowledged to be sparse, it was hypothesized that further examination of surface soil shear characteristics could be fruitful in explaining seasonal variability in soil erodibility.

The review of the development of soil erodibility theory demonstrates that none of the indices for soil erodibility proposed by various workers conform to the requirements for such an index: simple to measure, reliable and efficient in operation and capable of universal application both spatially and temporally. The relative failure of indices of erodibility may be attributed to incomplete and imprecise knowledge of the erosion process, of soil mechanics, and of the process of soil aggregate stabilization (Bryan, 1968). As current research provides new insights into these topics, it should prove possible to develop new and more efficient indices of erodibility.

3.2 THE FACTORS CONTROLLING SOIL ERODIBILITY

It has been demonstrated that a number of soil physical and chemical properties influence soil erodibility. The present study focuses on those characteristics affecting soil erodibility which were identified as important by the available literature, can be measured in the field or laboratory and are likely to be affected by cultivation. It must, however, be emphasized that these factors do not act in isolation, but that many complex interrelationships occur.

Soil water or moisture is an integral component of many processes within the soil, a major influence on several soil properties, and the critical resource in crop production (Pitty, 1978). Soil moisture is also a fundamental soil characteristic which affects many other soil attributes influencing erodibility, for example infiltration rate, aggregate stability and shear strength. Pall et al. (1982) identified high soil water contents as well as low soil density and shear strength values as the conditions leading to high soil erosion and transport rates during and immediately following spring thaw in two small drainage basins in Southern Ontario, Canada. Chepil (1956), however, in a study investigating factors controlling wind erosion, found that erodibility of a soil decreased as the square of the soil moisture increased up to 15 atmosphere percentage (approximately equal to the permanent wilting point) where no erosion occurred.

The precipitation which reaches the surface of the soil is directed along two possible routes - it either drains into the soil and enters the soil moisture store, or it remains on the surface and contributes to surface storage and flow. The relative proportions of precipitation following each of these routes depends to a large extent on the infiltration capacity of the soil. Infiltration capacity can be defined as the maximum sustained rate at which the soil can absorb water (Morgan, 1986). Because of its control on surface routing of water, infiltration exerts a fundamental influence on hydrological processes and therefore on soil erodibility. Agricultural effects on infiltration thus assume considerable importance. The infiltration capacity of the soil depends on the antecedent soil moisture, pore size and stability, the compaction of the soil and the inwash of fine materials into pore spaces. In general, light textured (sandy) or well structured soils have higher infiltration capacities than heavy or poorly structured soils.

During an intense storm, the infiltration capacity tends to decline as the surface layers of the soil become saturated. The water can then only infiltrate if the surface layers are emptied by drainage to depth. In addition, infiltration capacity may decline during rainfall due to both expansion of clay particles as they absorb water and also to clogging of soil pores by slaking of particles from aggregates (Briggs and Courtney, 1985). The infiltration capacity is therefore not constant for any one soil type. Marked spatial variations are also seen in infiltration rates during a storm. On the footslopes for example, infiltration rates are often limited by saturation of the soil due to downslope movement of water in the soil. This results in the preferential development of runoff in the footslope areas, while upslope the soil is still able to accept rainfall.

Since it is the infiltration capacity which ultimately determines the magnitude of runoff and the likelihood of erosion, it is possible that the soil erosion hazard would be lowest immediately after ploughing or the disturbance of the soil (due to decreased bulk density and increased porosity of the soil), increasing through time with the development of surface crusting or compaction.

Overland flow refers to the movement of water across the soil surface, either as sheetwash or as concentrated flow (Briggs and Courtney, 1985). In general, overland flow is produced by one of two processes. Hortonian or infiltration excess overland flow is produced in situations where rainfall intensities are greater than the infiltration capacities of the soil, resulting in the soil not being able to absorb all the incoming water. The excess water accumulates at the surface and flows downslope as sheetwash. Overland flow also occurs due to the local saturation of the soil surface. Such conditions are found in footslope areas where water is concentrated by lateral movement downslope. Rain falling on the surface of the soil may therefore be unable to infiltrate and will be ponded at the surface. In addition, water flowing from upslope may emerge above the saturated areas as seepage. Overland flow generated by these processes is known as saturated overland flow (Briggs and Courtney, 1985).

While these two types of overland flow show a distinct geographical distribution, both types of flow are produced on cultivated agricultural land. Infiltration excess overland flow may be common on compacted arable soils with low infiltration capacities or on soils which are susceptible to crusting (De Ploey, 1981).

The importance of aggregation in terms of erodibility is mainly due to its control on porosity in the soil and the type of surface it presents to precipitation (Pitty, 1978). Emerson (1967) states that the correlation between stability of soil aggregates and other physical properties is usually high, particularly with those properties related to erodibility and the infiltration and movement of water. The maintenance of water stable aggregates is essential if splash of particles is to be minimized. Infiltration is increased if the soil surface is in large aggregates, due partly to surface retention and partly to increased porosity. The amount of energy required to initiate runoff is a function of the size of aggregates in a tilled soil and large aggregates are equally important in delaying the time when runoff begins. The rapid decrease in infiltration resulting from low structural stability and consequent surface sealing may be largely offset by greater cloddiness after tillage (Pitty, 1978).

Shear strength is another measurable soil attribute that affects erodibility. The shear strength of a soil is a measure of its cohesiveness and resistance to shear forces exerted by gravity, moving fluids and mechanical loads (Morgan, 1986).
The shear strength of a soil is made up of three components (Briggs and Courtney, 1985):

1. Molecular cohesion derived from bonds between the particles;
2. Film cohesion derived from water bonds in the soil;
3. Friction which is a product of physical roughness and interlocking of the particles and aggregates.

In coarse-grained soils, it is the friction between grains that is important in determining shear strength. A high proportion of grains which are rough, jagged and interlocking will give the soil a high shear strength, and be able to bear a heavy load before shearing. In fine-grained soils, however, the cohesion between the grains is the most important factor. Because of this, moisture content is a major factor in determining the load-bearing properties of fine-grained soils. Fine-grained soils in the semi-solid state will exhibit stronger bonds between the particles and have a higher shear strength than similar soils in the plastic state (Courtney and Trudgill, 1984).

Soil texture is a factor influencing soil erodibility that can easily be measured in the field or laboratory. Texture is, however, the most permanent and fundamental soil property; it is changed little by man through soil management. It has considerable influence on soil structure, consistence, degree of compaction and stability, soil drainage and aeration and root penetration. It determines the ability of the soil to hold and exchange nutrients and it is a crucial factor in determining the soils response to fertiliser applications on agricultural land (Faniran and Areola, 1978). The role of texture is indicated by the fact that large particles are resistant to transport because of the greater force that is required to entrain them and that fine particles are resistant to transport because of their cohesion. The least resistant particles are therefore silts and fine sands (Morgan, 1986). Richter and Negendank (1977) have shown that soils with 40 to 60 per cent silt content are the most erodible. Evans (1980), however, indicates that soils with a restricted clay fraction, between 9 and 30 per cent, are the most susceptible to erosion. Clay content may therefore be a useful indicator of soil erodibility as clay particles combine with organic matter to form soil aggregates. It is the stability of these aggregates which determines the resistance of the soil. A high base content in a soil usually indicates a stable soil since the bases contribute to the chemical bonding in the soil. Wetting the soil may, however, weaken the aggregates by lowering their cohesiveness, softening the cements and causing swelling as the water is adsorbed on the clay particles (Morgan, 1986). Particle size analysis taken from the various soil horizons will indicate whether the ridging process has rearranged the horizons and exposed clays in the furrows.

The penetrometer is capable of detecting and quantifying differences in soil surface strength characteristics influencing the physical processes of water infiltration and soil erosion (Rolston et al., 1991). Soil penetrability can be defined as a measure of the ease with which an object can be driven into the soil (Bradford, 1986). The cone penetrometer is a useful method of determining and comparing relative strengths between soils as well as determining zones of compaction.

The changes in physical aspects of the soils under cultivation are essentially short-term changes which occur after only a few tillage operations, or a few years of cultivation. Over longer periods, more fundamental and less readily reversible changes may occur in the soil. One of these effects is seen in organic matter content. Organic matter improves cohesiveness, increases water retention capacity and promotes a stable aggregate structure. It is therefore a vital soil characteristic influencing soil erodibility. Soils with less than 2% organic carbon are considered erodible (Morgan, 1986). Voroney, van Veen and Paul (1981) have suggested that soil erodibility decreases linearly with increasing organic matter content over a range of 0 to 10 per cent. Morgan (1986), however, states that this cannot be extrapolated since some soils with high organic contents (peats) are highly erodible, and some soils with low organic contents become very hard and therefore stronger under dry conditions. Elwell (1986) showed that the erodibility of subtropical clay soils in Zimbabwe was dependent on clod size, which in turn, was dependent on organic content. Maximum clod size occurred at an organic content of 2.5%.

The main physical implication of both organic matter and micro-organisms are related to the development of soil structure (Briggs, 1977). The aggregation of soils is largely a result of electrochemical forces between colloid particles. These attract particles towards each other. Humus has a well developed surface charge and consequently contributes to the process of aggregation. Organic matter therefore acts as a vital store of available nutrients (Briggs, 1977).

The hormones, pesticides and herbicides that are applied to the soil and pineapple plants make a chemical analysis of soil pH and cation exchange capacity essential to a study of soil erodibility. However, little evidence exists in the literature on the effects of various chemicals.

From a chemical point of view, soil acidity is the most relevant characteristic in connection with pineapple cultivation (Py et al., 1989). Knowing the pH of a soil is extremely important for ensuring proper soil management. PH values show strong correlations with soil type, vegetation type, profile horizon and, agriculturally with crop growth, lime requirement and mineral nutrition (Etherington, 1975). Unless control of the pH is effective, even the ideal fertilization will not produce satisfactory results. The pineapple prefers acid (pH 4.5 to 5.5), weakly saturated soils and therefore maintaining the pH at the optimum values is difficult, particularly when the desired levels are low (Py et al., 1987).

In a controlled environment, potassium is more actively absorbed than calcium, nitrates better than sulphates. This results in acidification of the nutritive solution, irrespective of the initial pH. Py et al. (1989) reported that Godefroy (1975) demonstrated that repeated fertilization over a number of years can lead to acidification of not very saturated ferrallitic soils in The Ivory Coast. This evolution is most often linked to fertilization practices. In almost saturated but well-drained soils in areas of high rainfall, the balance can easily be upset by excessive quantities of acidifying substances such as nitrogen and potassium.

Perhaps the greatest general influence of pH is an indirect effect on soil fertility. This is a consequence of the effect of pH on the availability of nutrients (Figure 3.2).

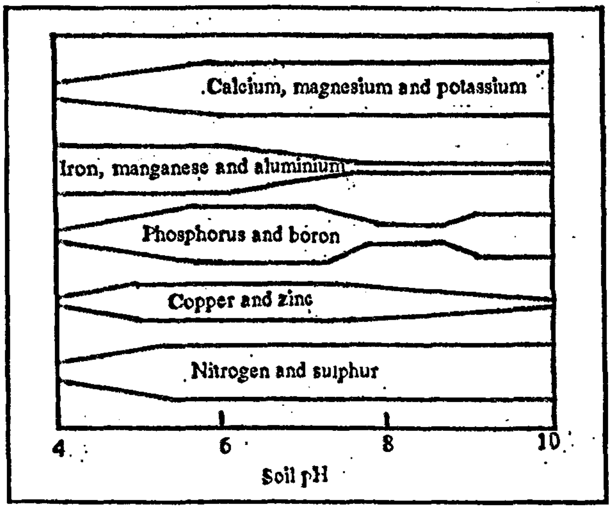


FIGURE 3.2: General relationship between soil pH and the availability of plant nutrients (Foth, 1978).

For example, calcium, magnesium and potassium are not readily available at a pH of lower than 6 (the optimal pH for pineapples is 5). A soil thus becomes acidic as Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} ions are leached from the profile faster than they are released by mineral weathering, and the H^{+} and Al^{3+} ions become predominant on the exchange surfaces (White, 1979). Another important point to bear in mind is that the value of soil pH can, in most normal soils be considered as an index of its exchangeable cation saturation. Most soils between pH 5.0 and 6.0 pass from approximately 25 to 75% saturation. Low pH is, however, particularly characteristic of cation unsaturated soils and nutrient deficiencies, particularly of divalent cations such calcium and magnesium may arise (Etherington, 1975). While no evidence exists in the literature stating that a nutrient deficient soil will have a higher soil erodibility, this is a distinct possibility. An example of this scenario is a sandy soil which is deficient in calcium having a higher soil erodibility as a consequence of the fact that calcium is a binder in sandy soils (Chepil, 1954). It is thus the associated conditions of a certain pH value that are the most important.

The best single index of potential soil fertility is its ability to exchange cations (Pitty, 1978). The ability of clays and humus to yield cations for plant use is called the cation exchange capacity (CEC) (Courtney and Trudgill, 1984). Exchangeable cations can be artificially changed to improve soils for crop production and engineering purposes, and cation exchange capacity is an index of the soils ability to adsorb biocides, for example herbicides. The CEC of a soil is, however, pH-dependent (White, 1979; Schroeder, 1984). It may be said that the CEC of sandy soils is associated mainly with their organic content but that of finer textured soils is a function of clay content (Etherington, 1975). The organic content variation, owing to its much higher CEC than clays, accounts for most of the variability in the CEC of soils as a whole. On loam-textured calcareous till soils in Ohio, the correlation between organic matter content and CEC was $r = 0.74$ ($N = 28$) (Wilding and Rutledge, 1966). Pitty (1978) reports several situations in which the correlation between CEC and organic matter content is sufficiently close for CEC to be predicted simply on the basis of organic matter content. It is, however, important to note the importance of local conditions which include the degree to which the topsoil has been eroded away. As B horizons of soils differ profoundly in their CEC characteristics, surface patterns will change considerably if these are exposed at the surface. Pitty (1978) reports a Miami soil series in Ohio in which the covariance of total clay and CEC is $r = -0.22$. The relationship is, however, converted to $r = 0.82$ in the B horizon. The CEC of humus is approximately twice that of pure clay, which emphasizes the importance of humus in soil fertility (Courtney and Trudgill,1984).

Individual cations are also important as they too influence soil erodibility. White (1979) states that cation leaching is accelerated in cultivated soils, where nitrification occurs. There are two basic reasons for this:

1. Nitrification is an acidifying reaction, so that H^+ ions are made available to displace exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+;
2. The increase in NO_3^- concentration must be balanced by an increased cation concentration in the water percolating through the soil.

The importance of calcium in influencing soil erodibility lies in terms of soil aggregation. The presence of calcium increases the aggregate stability of soils since divalent cations, such as calcium, are held more firmly by colloids than are monovalent cations, such as sodium (Evans, 1980). However, Chepil (1954) showed that, in general, calcium carbonate weakens soil structure and increases erodibility. Sandy soils, however, provide an exception because, as they have little structure in the first place, the addition of calcium carbonate is beneficial and acts as a weak cement. The sodium ion is the most mobile of all cations (Duchaufour, 1977) and is known to cause dispersion in clayey soils. Singer, Blackard and Janitzky (1980) discovered that sediment losses in sodium saturated Sacramento soils were three times the natural or magnesium saturated Sacramento soils. Treatment with magnesium or calcium actually reduced the amount of sediment lost in the Pescadero soil series. They conclude that sodium is important in predicting relative soil erodibility. Wallis and Stevan (1961) indexed the erodibility of some Californian soils using the dispersion and surface aggregation ratios, and tested values against concentrations of various soil cations by regression analysis. A negative correlation was found between erodibility and concentrations of calcium and magnesium as well as calcium + magnesium. No significant relationship was found with potassium and sodium.

Pitty (1978) views the CEC of a soil as the principal buffer mechanism in the soil. A buffer is a solution which minimizes changes which would otherwise occur towards either increasing acidity or alkalinity in the soil. The presence of calcium or magnesium is also important in maintaining near neutral conditions in the soil. In the tropics, however, minimal amounts of calcium in the soil mean that soils in the humid tropics are poorly buffered against changes. The practical significance relates to fertilizer applications which, particularly in poorly buffered soils, must be carefully balanced in both major and minor nutrients if chemical excesses or deficiencies are to be avoided.

3.3 THE IMPACT OF CULTIVATION ON FACTORS CONTROLLING SOIL ERODIBILITY

Recently, much attention has been focused on the effects of soil cultivation practices and ploughing on both the physical and chemical properties and processes in the soil (Strutt Report, 1970; Greenland, 1977; Russell, 1977; Briggs and Courtney, 1985 and Ross, 1989).

The traditional objectives of cultivation and ploughing practices were to drain and aerate the soil, to break up compacted zones and to suppress competing weed vegetation. Changes in soil structure and packing caused by ploughing initially alters soil physical properties such as soil moisture retention, bulk density and thermal regime. However, since these factors (particularly moisture and temperature) alter rates of chemical and biological activity in the soil, rates of organic matter decomposition and nutrient mobilisation are also likely to be affected by ploughing (Ross, 1989).

An additional factor that is important when assessing the effects of cultivation on soils is the influence of farm traffic such as tractors, harvesters and ploughs on the compaction of topsoils. The purpose of this section, therefore, is to examine the cultivation practices occurring and to assess their impact upon the factors that control the erodibility of soils.

Briggs and Courtney (1985) state that there is a tendency for cultivated soils to lose water more rapidly by gravitational drainage (at least from the upper layers) than uncultivated soils. This has two important consequences. Firstly, it means that there is less likelihood of waterlogging in the surface horizon (vital for pineapple lands), and the field capacity of the soil occurs at a relatively low moisture content. Secondly, the soil as a whole retains less water after rainfall and therefore has a smaller capacity to store water (a reduced available water capacity). Exceptions can, however, occur as a result of untimely tillage. Development of a plough-pan may greatly reduce drainage in the topsoil and cause water-logging. Preventing the rapid removal of gravitational water will affect infiltration rates. During prolonged rainfall, saturation of the topsoil may occur due to impeded drainage and saturated overland flow may take place.

Van Ouwerkerk and Boone (1970) have suggested that it is the alteration of pore size distribution during tillage, causing a loss of large pores and a predominance of small pores, that influences moisture retention after ploughing. Hill, Horton and Cruse (1985) state that more moisture is retained over a large suction range in untilled soils than is retained in conventionally tilled soils. Negi, Raghavan and Taylor (1981) confirm this finding. Their crop yield and root growth studies imply that zero tilled soils contain up to twice as much plant-available water compared to conventionally tilled soils. This suggests a predominance of medium sizes pores in zero tilled soils.

Most tillage operations such as ploughing and ridging result in some rearrangement of the aggregates, which causes the opening up of pore spaces and fissures. Consequently, the ploughed layer of tilled cultivated soils tends to be looser, less dense and more porous than that of untilled virgin soils. Breakup of soil structure can, therefore, initially lead to reduced bulk density and increased porosity of surface soils where the material is loosened (Ross, 1989). Soane and Pidgeon (1975) found that both shallow and deep forms of conventional ploughing resulted in lower bulk densities and higher porosities than zero or minimum tillage techniques. Pidgeon and Soane (1977) in a 7-year spring barley field experiment on a sandy loam, found that no bulk density changes occurred under continuous zero tillage after the first three years. This condition thus marks an equilibrium bulk density between a particular soil and imposed management practice.

Exceptions can occur whereby the densities of tilled soils can increase significantly. A possible reason for this is that tillage under unsuitable moisture conditions may lead to compaction of the surface soil. This is mainly due to the effect of vehicular wheel traffic (Figure 3.3) (Soane, 1975; Voorhees and Lindstrom, 1984).

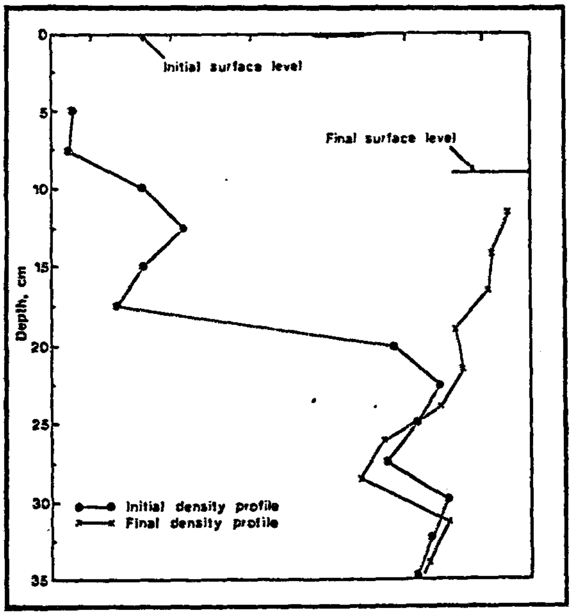


FIGURE 3.3: Changes in bulk density with depth following the passage of a tractor on loose soil (Soane, 1975).

Campbell, Dickson and Ball (1982) studied the effect of number of tractor wheel passes on soil physical properties at 30 mm depth on a sandy clay loam and discovered that air filled porosity decreases by more than 50% after a single wheel pass. Increases in bulk density were also recorded (Figure 3.4).

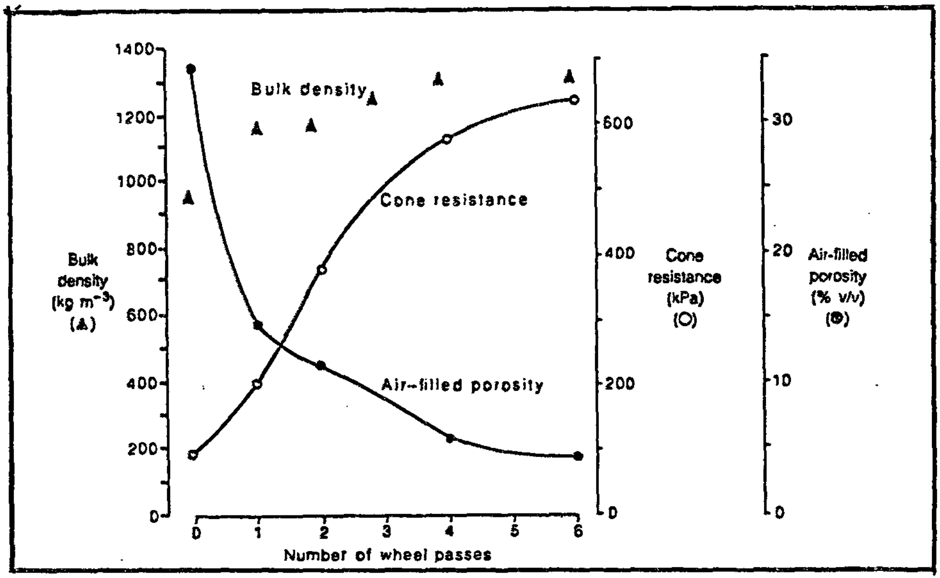


FIGURE 3.4: Effect of number of tractor wheel passes on soil physical properties at 30 mm depth on a sandy clay loam (Campbell, Dickson and Ball, 1982).

Thus, while tillage commonly loosens the upper layers of the soil, at depth, the reverse may occur where bulk densities increase in the lower part of the plough layer. This may again be due to compression by tractor and implement wheels, but it may also result from the development of a plough-pan. Repeated tillage, at a similar depth, may cause the formation of a smeared and compacted layer. This inhibits water and air movements and prevents root extension.

Foth (1978) reports a study of the effects of growing cotton for 90 years on clay-textured Houston soils in the Texas blacklands. Soil samples from cultivated fields were compared with samples obtained from an adjacent area that had remained in grass. Long-term cultivation caused a significant decrease in soil aggregation and total pore space and an increase in bulk density. These changes are shown in Figure 3.5. The most striking and important change was the decrease in macropore space which was reduced to about half of that of the uncultivated soil. Changes in total pore space parallel the changes in bulk density. Foth (1978), however, does not suggest any reasons for these findings. The increased bulk density and reduction of air-filled porosity may nevertheless be a consequence of compaction.

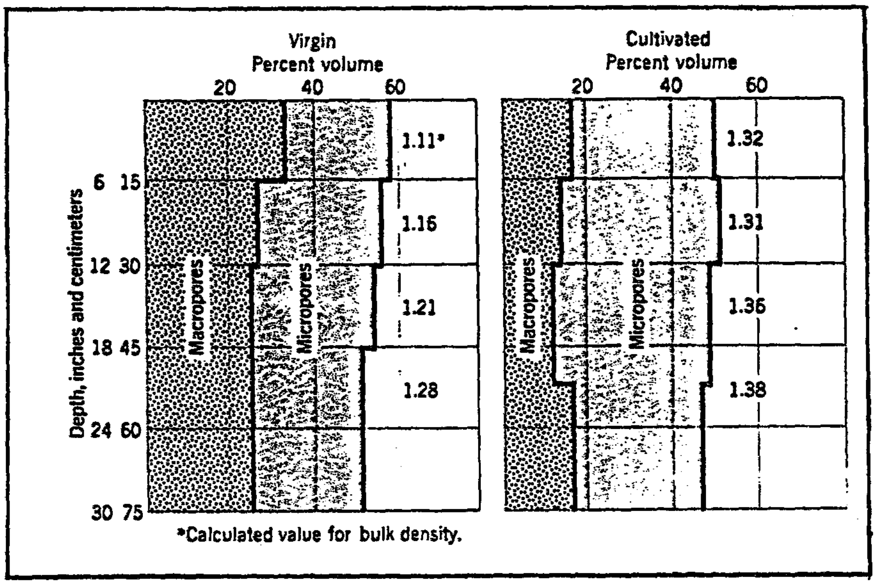


FIGURE 3.5: The effects of 90 years of cultivation on pore space and bulk density of Houston soils (Foth, 1978).

Cultivation practices affect infiltration processes in a wide variety of ways. Cultivation, through its control on vegetation cover, influences interception and therefore the amount of water available for infiltration. Ploughing generally loosens the soil surface and increases the volume and connectivity of pores, increasing infiltration capacities. Compaction by wheel or foot traffic leads to closure of pores and reduced infiltration capacities. Subsurface compaction (plough-pans) encourages water retention in the surface layers, leading to reduced rates of saturated infiltration. In the longer term the effects of cultivation, crop removal and manurial treatments on soil organic matter content and aggregate stability affect the structure of the soil and thus affect infiltration capacity.

Burning of vegetation to clear fields may reduce infiltration capacity, not only because it leads to a loss of organic matter, but also because ash is washed into the surface pore spaces (Biederbeck et al., 1980). For similar reasons, the choice of cropping system significantly influences infiltration capacity. Crops which leave the soil bare for long periods (for example, pineapples) encourage surface slaking and pore sealing, while those crops which add large amounts of organic matter to the soil, produce extensive root systems and give good protection against rain-splash and increase infiltration capacity (Briggs and Courtney, 1985).

One of the major influences of infiltration capacity is the nature of the soil surface. Steichen (1984) investigated various levels of ploughing intensity and confirmed the fact that enhanced surface roughness immediately after ploughing and the presence of a surface mulch both increase infiltration capacity. The untilled soil consistently showed the lowest infiltration rates, partly due to the fact that the soil was untilled. Infiltration rates in ploughed soils usually decline through time due to the development of a surface soil crust by rainfall impact after aggregate disruption during ploughing (Ross, 1989).

Gifford and Hawkins (1978) have shown that infiltration rates on grassland are generally higher than those on arable land. The infiltration capacity usually increases as the pasture gets older due to the accumulation of organic matter at the surface and the development of an extensive root system and stable soil structure.

Agricultural practices therefore exert great control on the generation of overland flow. Overland flow has considerable significance agriculturally because it is highly erosive and also removes seeds, fertilisers and pesticides. In general, processes which increase rainfall interception and infiltration capacity of soils may be expected to reduce the incidence and magnitude of overland flow. Also, practices which encourage water depletion by evapotranspiration or drainage diminish losses by overland flow. As a result, overland flow tends to decline with increasing crop cover or with greater retention of plant residues (Adams et al., 1978). Briggs and Courtney (1985) report differences in runoff resulting from different cropping systems. Runoff, expressed as a percentage of rainfall, was least from continuous grass, intermediate from rotation crops and greatest from continuous maize. The results indicate that runoff is inversely related to vegetation and directly related to the frequency of cultivation.

Overland flow from grassland or natural vegetation is generally less than that from cultivated land. A grass sward provides a more or less continuous vegetation cover which intercepts rainfall and impedes any overland flow which does occur. The improved rooting and organic matter accumulation also means that infiltration capacity tends to be higher than in arable soils (Ross,1989).

Stability of soil aggregates under rainfall plays an important role in determining the magnitude of soil loss from cultivated fields (Truman et al., 1990). Disruption of soil structure has been widely reported. Low (1955) compared structural stability under permanent grassland and arable cropping, and noted a decline in stability from 73 to 35 per cent after only a single year of arable cultivation. Similarly, Dettman and Emerson (1959) found structural stability levels low as 5 per cent in unmanured cultivated land compared to 50 per cent in land that had been down to grass for 4 years. A more recent study by Low (1972) considered the pattern of structural disruption for ploughed out grassland. A rapid decrease in stable aggregates occur in the first year after ploughing with a less dramatic decline in subsequent years (Figure 3.6).

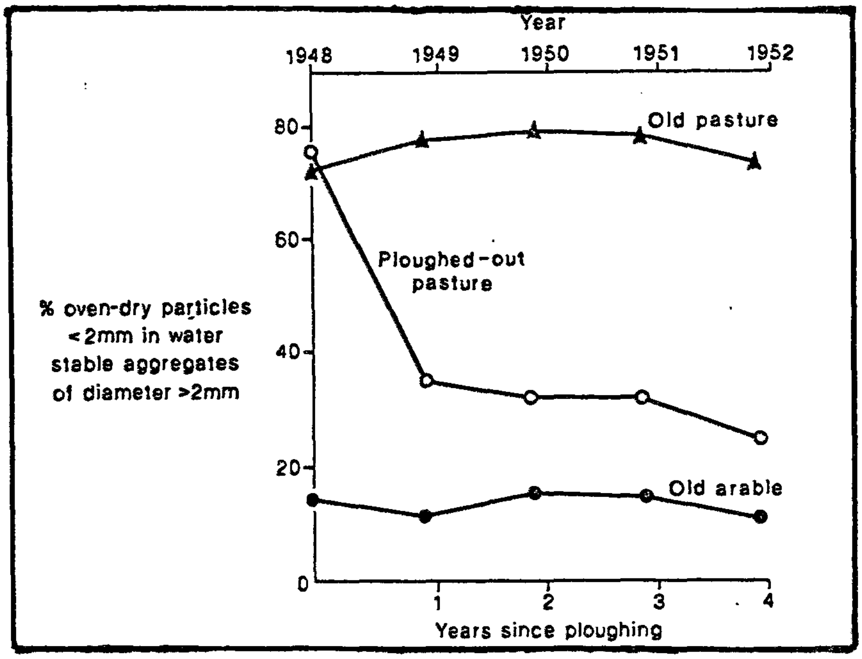


FIGURE 3.6: Changes in water stable aggregates after ploughing old pasture compared to remaining old pasture and old arable sites on the same soil series (Low, 1972).

The results of a number of field trials by Low (1972) indicate a consistently higher degree of aggregate stability in virgin soils than in ploughed or cultivated soils. Both Elliot (1984) and Powers and Skidmore (1984) conclude that the major effect of cultivation is the reduction in the size and stability of macro-aggregates. The loss of aggregated material is possibly due to the enhanced organic matter decomposition that occurs after ploughing (Ross, 1989). Ross (1989) reports that zero tillage practices are generally found to increase structural stability and organic matter content compared to conventional ploughing, particularly in the surface soil horizons. Improved aggregate stability compared to conventional ploughing is, however, partly a result of increased organic content. Increased surface organic matter content results from crop residues being left in situ after harvesting to form a mulch. This is a common practice in the United States to reduce soil erosion (Ross, 1989).

The implications of the loss of aggregate stability are multiple. One inevitable result is that the soil becomes more prone to capping and crusting under the impact of rainfall. Additionally and most importantly, the reduced stability makes the soil susceptible to erosion by both wind and water (Chepil, 1955; Johnson et al., 1979). Structural stability is therefore one of the main controls on erodibility.

Reduced stability of aggregates is reflected by lower molecular cohesions and as a result, the aggregates may be liable to shearing even at low moisture contents. Structural deterioration as a result of excessive tillage thus triggers off positive feedback processes that make the soil progressively more prone to damage and more difficult to cultivate (Figure 3.7).

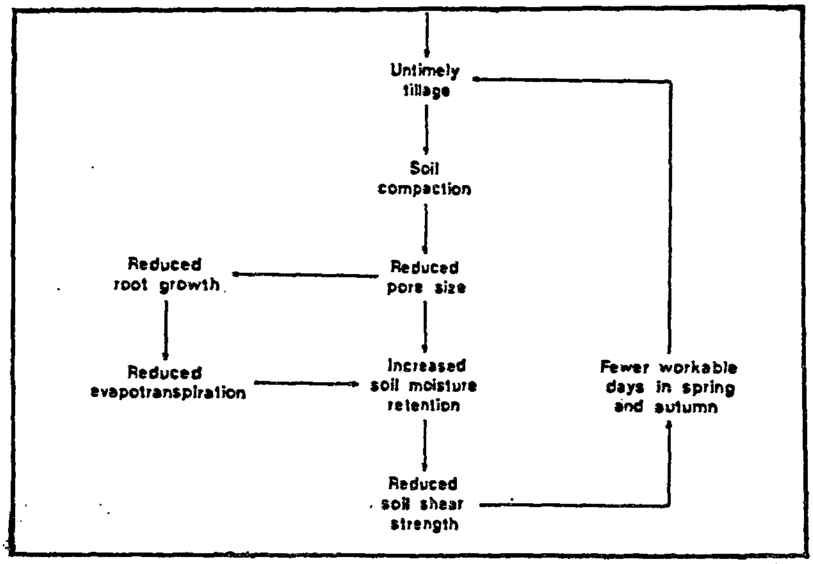


FIGURE 3.7: Feedback effects of soil compaction due to untimely tillage (Briggs and Courtney, 1985).

In soils of low structural stability, timeliness of cultivation is therefore of major importance.

Simple cone penetrometer resistance values for mechanical impedance have also been used as index for the suitability of ploughed soil for root penetration (Ross, 1989). This is a reproducible, although somewhat unrealistic assessment since it is difficult to simulate root exudates that reduce friction and ease the root's passage through the porespace. Campbell, Dickson and Ball (1982) have shown that mechanical impedance measured by cone resistance nearly trebles with just three vehicle wheel passes (Refer to Figure 3.4).

Various authors have shown that tillage of grassland leads to a slow, but persistent decline of organic matter (Clements and Williams, 1964; Jenkinson and Johnson, 1977 and Russell, 1977). Arable soils often contain no more that 1-2 per cent organic carbon whereas pasture soils contain approximately 5-10 per cent organic carbon (Figure 3.8).

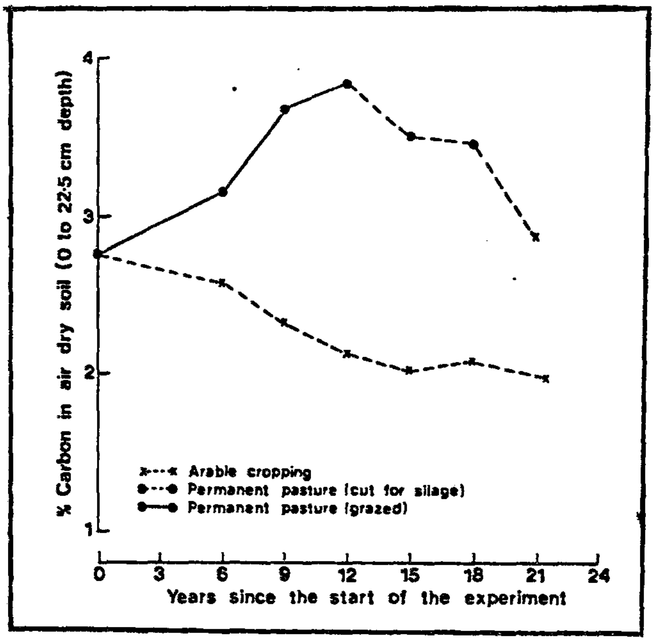


FIGURE 3.8: Changes in the organic carbon content of arable and pasture soils in the Highveld ley-arable experiment (Johnston, 1973).

During conventional ploughing, soil structural disruption and the altered diurnal temperature regime are considered to be important factors in increased organic matter decomposition and nutrient mineralisation.

Rovira and Graecen (1957) were the first to show that biological degradation of organic matter in soil aggregates is just as important as physical disruption in reducing structural stability. During the disaggregation of soil structure which follows ploughing, Powers and Skidmore (1984) suggest that insoluble, organic bonds and bridges between aggregates are broken up by mechanical disruption. Since these organic bonds are responsible for aggregate stability, Powers and Skidmore (1984) found that all compressed and disturbed soils in their experimental cultivations showed poorer wet and dry aggregate stabilities than surface soils. Similar results were found by West et al. (1991). After 5 years of cultivation, the 0 - 0.015 m layer of soils under a no-till system had more than twice as much as organic carbon (10 versus 23 $g.kg^{-1}$) and 35% (51 versus 87%) more water stable aggregates than soils managed under conventional tillage.

Ross (1989) states a case of when after laboratory simulated tillage, increased oxygen uptake was attributed to the exposure to decomposer microorganisms of organic matter which was previously inaccessible in ped centres. Greater intensities of simulated tillage, and hence disruption, increased the availability of organic matter. The resultant higher rates of oxygen uptake were due to the increased activity of decomposer microorganisms. Although this effect was shown in both virgin and previously cultivated soils, the magnitude of microbial activity following simulated tillage was higher in previously undisturbed soils.

An important consequence of the loss of organic compounds that accompanies cultivation is reduced cation retention and diminished cation exchange capacity (Kulkarni and Savant, 1977). This may lead to a marked reduction in the quantity of plant-available nutrients in the soil. Williams and Lipsett (1961), comparing soils under pasture and under arable rotations, noted a 30 per cent decline in organic matter content after 20 rotations, and an associated fall of 30 per cent in nitrogen and sulphur contents, a 14 per cent reduction in sodium, calcium, magnesium and potassium, and a 17 per cent decline in phosphorus content.

The preceding discussion has illustrated the multi-dimensional nature of potential factors controlling erodibility and the impact of cultivation and agricultural management practices on soil factors controlling erodibility.

CHAPTER 4
METHODS OF DATA COLLECTION AND ANALYSIS

Based on information gained from the literature (Chapters 2 and 3) and the pilot study (Chapter 1), a number of soil characteristics were selected for examination. The selected soil characteristics (Table 4.1) are all considered important factors controlling the erodibility of soils. Random sample grids were drawn up for each of the four sample sites (traffic, ridge, furrow and natural vegetation) within the two study areas representing the Glenrosa and Oakleaf soil forms (Appendix A). The sample points were marked to ensure that the sampling of each soil characteristic occurred at exactly the same position for each sample point. The number of samples collected for each soil characteristic is shown in Table 4.1. The number of samples collected varied due to temporal and financial constraints.

A soil profile description was completed at each of the four sites in both soil forms (Appendix B). This was to ascertain that the Oakleaf/Glenrosa soil form did in fact occur in each of the four sample sites. Soil samples for the measurement of soil moisture, bulk density, porosity, aggregate stability, soil texture, organic carbon, pH and cation exchange capacity were collected using the metal ring sampler technique for taking undisturbed samples (Foth et al., 1982). All soil samples were collected to a depth of approximately 10 cm. Since the antecedent soil moisture conditions would affect many of the factors influencing soil erodibility, the rainfall data for a two week period preceding sampling was monitored. No significant rainfall events occurred in the two week period before the 14 - 18 July 1990 (Glenrosa sampling period) and the 17 -21 November 1990 (Oakleaf sampling period).

TABLE 4.1: Number of samples for the various soil characteristics controlling soil erodibility.

	Oakleaf soil form				Glenrosa soil form				Method used
	T	R	F	V	T	R	F	V	
Soil Moisture	60	60	60	60	60	60	60	60	Gravimetric
Bulk Density	60	60	60	60	60	60	60	60	Gravimetric
Porosity	30	30	30	30	30	30	30	30	Particle density
Infiltration Rate	10	10	10	10	10	10	10	10	Single ring Infiltrometer
Aggregate Stability	30	30	30	30	30	30	30	30	Volume change on immersion
Shear Strength	30	30	30	30	30	30	30	30	Shear vane
Soil Texture	15	15	15	15	15	15	15	15	Hydrometer
Soil Structure	-	1	1	1	-	1	1	1	Field description
Penetrability	10	10	10	10	10	10	10	10	Penetrometer
Organic Carbon	30	30	30	30	30	30	30	30	Walkley-Black
pH	30	30	30	30	30	30	30	30	Electrometric
CEC	1	1	1	2	1	1	1	2	Ammonium acetate

where T = traffic area

R = pineapple ridge

F = pineapple furrow

V = natural vegetation

4.1 DATA COLLECTION OF SOIL PHYSICAL CHARACTERISTICS

4.1.1 SOIL MOISTURE

A number of techniques, including those using agar blocks and nuclear devices, exist for the measurement of soil moisture. However, the gravimetric method of soil moisture analysis was adopted since it remains the only direct method of measuring soil moisture.

The major advantage of using the gravimetric method includes the fact that it is a simple approach that may be carried out using standard laboratory equipment. A disadvantage of the gravimetric method is that it is a destructive method. Another drawback is that a great deal of physical effort and time must be spent during collecting, weighing and drying of samples and the calculation of the results (Reynolds, 1970).

The method involves taking a soil sample, recording its weight, drying the sample in the oven and then reweighing the sample. The dry soil mass is determined after drying to a constant weight (for at least 24 hours) at 105°C. The soil moisture is expressed as a percentage of the oven dry weight of the soil:

$$\% \text{ Soil Moisture} = \frac{\text{Wet soil mass - Dry soil mass}}{\text{Dry soil mass}} \times 100 \quad \text{(E4.1)}$$

Further details of this method are presented by Gardner (1986).

4.1.2 BULK DENSITY

The bulk density of a soil is the ratio of its mass to its volume (Briggs, 1977). The bulk volume includes the volume of the solids and of the pore space. The mass is determined after drying to a constant weight at 105°C, and the volume is that of the sample as taken in the field (Blake and Hartge, 1986).

Bulk density is expressed by the relationship:

$$\text{Bulk Density (g.cm}^{-3}\text{)} = \frac{\text{Dry mass of soil}}{\text{Volume of soil}} \quad \text{(E4.2)}$$

The two main factors affecting this relationship are composition and packing of the soil. Most of the minerals which make up the soil, for example quartz, have a density of approximately 2.65 $g.cm^{-3}$ while organic matter has a density of approximately 0.4 $g.cm^{-3}$. Increased organic content will therefore result in a lower bulk density of a soil. Most mineral soils have a bulk density of approximately 1.25 $g.cm^{-3}$. Variations in the packing of soil particles are, however, also important. Mineral soils may show a range from 1.0 to 2.0 $g.cm^{-3}$ as a result of differences in the volume of voids (Briggs, 1977).

The procedure adopted made use of the bulk density core-cutter to obtain a soil sample. The soil was transferred to a container, dried in an oven at 105°C until a constant weight was reached and weighed. The bulk density was the oven dried mass of the sample divided by the sample volume. A more detailed account of this procedure can be found in Blake and Hartge (1986).

4.1.3 POROSITY

Soil structure can be measured in various ways, but perhaps it is most meaningfully evaluated through some knowledge on the number, size and distribution of pores (Danielson and Sutherland, 1986). Porosity is a value expressing the percentage of a soils volume that is occupied by pore spaces. Porosity is not measured directly, but is calculated using measures of bulk and particle density. Porosity is therefore expressed by the equation:

$$\text{Percentage Pore Space} = 100 - \left(\frac{\text{Bulk Density}}{\text{Particle Density}} \times 100\right) \quad \text{(E4.3)}$$

Details of the gravimetric method of bulk density determination are presented by Danielson and Sutherland (1986).

The particle density of soils refers to the density of the solid particles collectively. It is expressed as the ratio of the total mass of solid particles to their total volume, excluding pore spaces between particles. The particle density of a soil is therefore the composite average of the densities of all the minerals found in soils. For most soils this value is 2.65 $g.cm^{-3}$.

Particle density was determined using the pycnometer method. However, since only one pycnometer was available, volumetric flasks were used. The pycnometer method was chosen over the submersion method since the pycnometer method has the advantage of giving very precise densities if volumes and weights are carefully measured. Particle density is expressed by the relationship:

$$\text{Particle Density } (g.cm^{-3}) = \frac{\text{Mass of particle}}{\text{Volume of particle}} \qquad \text{(E4.4)}$$

Blake and Hartge (1986) present further particulars on the pycnometric method of particle density determination.

4.1.4 INFILTRATION RATE

Infiltration rate may be defined as a measure of the quantity of water infiltrated per unit time (Hills,1970). The single cylinder infiltrometer method was adopted since a double ring infiltrometer was too large to fit on the ridges or in the furrows of the pineapple lands. Burgy and Luthin (1956) have shown that the concept behind the double cylinder system, that the outer, annular space between the two rings absorbs the edge and divergence effects, is erroneous. Burgy and Luthin state that there is little difference between the infiltration rate from the inner cylinder and that of the larger cylinder alone. Increasing the size of the infiltrometer is the only way to reduce the effect of lateral divergence of flow below the cylinder (Bouwer, 1986). However, the diameter of the infiltrometer was limited by the diameter of the furrow, and therefore a single cylinder infiltrometer with a diameter of 30 cm, a height of 20 cm and a penetration depth of 5 cm was used. Since only cylinders with diameters of greater than 1 m yield accurate measurements, the infiltration data must be viewed with caution. The actual method used was adapted from Young (1980). The cylinder infiltrometer was placed in the soil and 2 l of water was carefully poured into the cylinder. The infiltration time was recorded. A simple calculation was then used to determine the infiltration rate in ml. $minute^{-1}$. This method was used since it was not too time consuming.

The use of the small, single cylinder for infiltration measurement is easily justified in terms of cost, convenience and replicability. They are inexpensive to construct, hand portable and require only small quantities of water. However, Hills (1970) states that this technique has been subject to intense criticism for a number of reasons:

1. Disturbance of soil during emplacement;
2. Lateral flow of the water underneath the cylinders;
3. Water seepage down the cylinder-soil interface;
4. The effect of air within and underneath the cylinder.

The sources of error described can be minimised by careful use and a sensible sampling design, but they can never be eliminated. However, since only relative measurements between the four sample sites are needed, the small, single cylinder method is adequate.

4.1.5 AGGREGATE STABILITY

The stability of peds is an important property influencing soil erodibility. Soil aggregates tend to be more stable when dry than when wetted since water entering the aggregates disrupts the electrochemical forces which cause the soil particles to cohere to one another. Water may also dissolves the cements which bind and stabilize some soil aggregates (Briggs, 1977). Aggregate stability may therefore be considered as a measure of a soils resistance to breakdown upon wetting. The stability of aggregates thus depends on whether the cohesive forces between particles can withstand the applied disruptive force (Kemper and Rosenau, 1986).

Measurement of aggregate stability provides a direct measure of the susceptibility of the soil to structural deterioration under the influence of rainfall and other forces causing disintegration in the field. However, the disintegration forces occurring during sample collection, preparation and analysis do not duplicate the field phenomena. Consequently, the relationship between aggregate stability obtained in the laboratory and existing in the field is empirical and must be viewed with caution.

Various methods occur to determine aggregate stability, but the equipment for most methods is usually very costly. For this reason, a simple method outlined by Briggs (1977) which examines the behaviour of soil peds on wetting was chosen. The procedure adopted was as follows:

1. A 50 g soil sample was placed on a 2 mm sieve and agitated gently.
2. The soil retained on the sieve (aggregates) was poured into a graduated cylinder and gently tapped to settle the soil.
3. The volume of the soil was noted and recorded as V1.
4. The beaker was filled with water to the 50 ml mark, taking care not to damage the aggregates.
5. The sample was allowed to stand for 30 minutes after which the water was carefully poured off.
6. The beaker was again tapped gently and the volume of the soil was recorded as V2.
7. Aggregate stability was obtained from the following equation:

$$S(\%) = \left(1 - \frac{V1 - V2}{V1}\right) \times 100 \qquad \text{(E4.5)}$$

4.1.6 SHEAR STRENGTH

The shear vane test was used to give a rapid estimate of the shear strength of the soil (British Standards Institute, 1975). The readings were obtained by embedding the vane blades in the soil and applying a steadily increasing torque to the circular rod. Failure of the soil takes place and a reduction of the torque required is noted. This point at which the torque required decreases, gives an indication of the shear strength of the soil.

A limitation of this method is that the shear vane was developed for undrained, fine-grained soils. The British Standards Institute (1975) emphasized this by stating that the test was suited to very soft to firm non-fissured, saturated, cohesive soils. As a result of the compaction occurring in the pineapple lands (particularly in the traffic area), it was extremely difficult to embed the vane blades in the soil. Where soil disturbance occurred, the values were discarded as erroneous. Further details of the shear vane test can be found in the British Standards Institute 1377 (1975).

4.1.7 SOIL TEXTURE

The texture of a soil can be accurately determined by particle size analysis. Particle size distribution represents a stable soil property and is related to physical and chemical activity in the soil. There is also a direct relationship between particle size and the amount of surface area present in a given weight of soil (specific surface area). Since most physical and chemical properties of the soil are associated with surface activity, particle size distribution has become a standard method of classifying and characterizing the soil particles (Briggs, 1977).

The most widely used techniques of soil particle size analysis are the hydrometer and pipette methods. The hydrometer method was adopted since it is a simple method and less time consuming than the pipette method. Walter et al. (1978) compared pipette and hydrometer measurements of the 2μm size fraction in glacial till soils and found agreement within 5%. Liu et al. (1966) also found agreement between the pipette and hydrometer analysis. Calculated correlation coefficients (r values) varied between 0.90 and 0.99 for 155 soil samples from 11 states. The results of Walter et al. and Liu et al. confirm that pipette and hydrometer methods provide comparable results.

The Bouyoucos hydrometer method, which separates soil particles into different size ranges based upon their differential settling rate in water, was adopted. This technique was developed by Bouyoucos (1934) and remains the basic routine method for determination of particles sizes in soils (Smith and Atkinson, 1975).

The basic procedure was as follows:

1. The pretreatment involved using hydrogen peroxide to remove organic matter
2. The solution was dispersed using Calgon
3. The suspension was shaken vigorously
4. The hydrometer was inserted and a reading was taken exactly 40 seconds after shaking was stopped (R1)
5. The second hydrometer reading was taken exactly two hours later (R2)

Percentages sand, silt and clay were calculated according to the following formulae:

$$\% \text{ Sand} = \frac{W - R1}{W} \times 100 \qquad (E4.6)$$

$$\% \text{ Silt} = \frac{R1 - R2}{W} \times 100 \qquad (E4.7)$$

$$\% \text{ Clay} = \frac{R2}{W} \times 100 \qquad (E4.8)$$

where W was the mass of soil used (g).
The hydrometer readings were adjusted by adding 0.3 g of soil for every 1 degree C above 20°C, or subtracting 0.3 g of soil for every 1 degree C below 20°C (Briggs, 1977).

Although the hydrometer method is an extremely accurate yet simple technique of textural analysis, there are several sources of error and difficulty which need to be considered:

1. It is essential to exert extreme care when lowering the hydrometer into the suspension and when raising it. During both procedures, some disturbance of the suspension occurs, and it is necessary to minimise this as much as possible.
2. Gee and Bauder (1986) state that although the Bouyoucos procedure has been used by a number of laboratories, the 2 hour reading does not yield correct estimates of the 2 μm clay fraction. Based on theoretical considerations, the 2 hour hydrometer reading is a closer estimate of the 5 μm silt fraction than it is of the 2 μm clay fraction. Therefore, errors in clay content using the 2 hour reading often exceed 10 wt% for clay soils.

Gee and Bauder (1986) provide more information on the hydrometer method of particle size determination.

4.1.8 SOIL STRUCTURE

Although bulk density, aggregate stability and shear strength measurements give some indication of soil structure, a structural classification was completed on the soil profiles. Soil structure refers to the aggregations of primary soil particles into compound particles or clusters of primary particles. These particles are separated from adjoining aggregates by surfaces of weakness (Faniran and Areola, 1978).

The importance of soil structure in influencing soil productivity cannot be overemphasized. The capability of any soil for the growth of plants and its response to management depends as much on its structure as on its fertility.

Field descriptions of soil structure note the distinctness and durability of the visible aggregates as important characteristics. Soils can be classified according to the grade, the size and the shape of aggregates (Hartmann, Hall and Dekker, 1989):

Grade:

1. Single grain - non coherent with no observable aggregation and no orderly arrangement of natural lines of weakness.
2. Massive - as for single grained but coherent.
3. Weak - peds barely observable in place and when disturbed few entire peds are observed, much of the material being unaggregated.
4. Moderate - peds easily observable, but not distinct in place and when disturbed many entire peds are observed with little unaggregated material.
5. Strong - peds are distinctly visible in place and when disturbed nearly the whole mass consists of entire peds.

Size:

No entry when structureless

SIZE	CLASS	BLOCK DIAMETER (mm)	GRANULE DIAMETER (mm)	PRISM DIAMETER (mm)	PLATE THICKNESS (mm)
1	Fine	<10	<2	<20	<2
2	Medium	10-20	2-5	20-50	2-5
3	Coarse	>20	>5	>50	>5

TABLE 4.2: Soil structure classification according to size (Hartmann, Hall and Dekker, 1989)

Shape (Refer to Table 4.3):

1. Structureless or apedal - no observable aggregation or no orderly arrangement of natural lines of weakness.
2. Blocky angular - all 3 dimensions of the same order of magnitude, faces flattened, most vertices sharply angular, faces accommodate adjacent peds.
3. Blocky subangular - as for blocky angular but both rounded and flattened faces occur with many rounded vertices.
4. Spheroidal or granular - approximately spherical with no accommodation of faces to surrounding peds.
5. Prismatic or columnar - vertical faces well defined, vertical exceeds horizontal dimensions, faces accommodate those of adjacent peds.
6. Platy - vertical dimension small relative to horizontal dimension, faces accommodate those of adjacent peds.

(Hartmann, Hall and Dekker, 1989)

4.1.9 PENETRABILITY

Soil penetrability is a measure of the ease with which an object can be pushed or driven into the soil (Bradford, 1986). Any device designed to measure resistance to penetration may be called a penetrometer.

Two basic types of penetrometers exist:

1. The dynamic penetrometer (penetration is accomplished by driving the tool into the soil with a falling weight)
2. The static penetrometer (the probe is pushed steadily into the soil without impact)

Although Bradford (1986) states that the dynamic method has found limited application in soil science, a dynamic cone penetrometer was used since it was the only type available for the study.

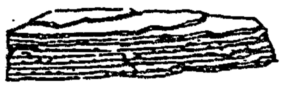
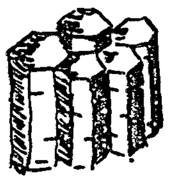
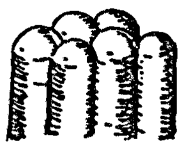
Kind of Structure	Description		Horizon
Crumb 	Aggregates are small, porous, and weakly held together	Nearly spherical, with many irregular surfaces	Usually found in surface soil or A horizon
Platy 	Aggregates are flat or plate-like, with horizontal dimensions greater than the vertical. Plates overlap, usually causing slow permeability		Usually found in subsurface or A_2 horizon of timber and claypan soil
Angular Blocky or Cube-Like 	Aggregates have sides at nearly right angles, tend to overlap	Nearly block-like, with 6 or more sides. All 3 dimensions about the same	Usually found in subsoil or B horizon
Prismatic 	Without rounded caps	Prism-like with the vertical axis greater than the horizontal	
Columnar 	With rounded caps		
Structure Lacking, Single Grain	Soil particles exist individually (as in sand) and do not form aggregates		Usually found in substratum or C horizon
Massive	Soil material clings together in large uniform masses (as in loess)		

TABLE 4.3: Soil structure classification according to shape (Hartmann, Hall and Dekker, 1989)

The basic procedure was as follows:

1. Care was taken that the penetrometer was held as vertically as possible and that the hammer was allowed to fall under the influence of gravity only.
2. A maximum of 60 blows were delivered to each sample point, since allowing the penetrometer to sink to its maximum depth was too time consuming. After each blow the relevant depth was recorded.
3. If the penetrometer reached the maximum depth before 60 blows, the penetrometer was simply removed from the soil, with the relevant data being recorded.

The dynamic cone penetrometer is therefore a useful method of indexing relative strengths among similar soil types or in determining zones of compaction. Bradford (1986) discusses the penetrometer method in more detail.

4.2 DATA COLLECTION OF SOIL CHEMICAL CHARACTERISTICS

4.2.1 ORGANIC CARBON

Carbon is the chief element present in soil organic matter, comprising from 48 -58% of the total weight (Nelson and Sommers, 1986). Organic carbon is contained in the soil organic fraction, which consists of the cells of microorganisms, plant and animal residues at various stages of decomposition, humus synthesized from residues and highly carbonized compounds such as charcoal, graphite and coal (elemental forms of C).

Two methods are commonly used for determining organic C:

1. Based on quantitative combustion procedures wherein C is determined as CO_2;
2. Based on the reduction of the dichromate ion ($Cr_2O_7^{2-}$) by organic matter wherein the unreduced $Cr_2O_7^{2-}$) is measured by titration.

The combustion methods are time consuming and require complicated sets of apparatus, hence the titration method was adopted for this study.

The titration method used was the Walkley-Black method (1934). This method is simple, rapid, widely used and requires minimal equipment (Nelson and Sommers, 1986). The organic matter in the soil is oxidised by potassium dichromate. This reaction is facilitated by the heat generated when concentrated sulphuric acid is added. The excess dichromate not used up in the oxidation is determined by titration with standard ferrous ammonium sulphate.

The amount of organic C oxidised is calculated from the amount of dichromate reduced. This value is expressed as a percentage of the dry weight of soil used (Faniran and Areola, 1978).

Titration methods, in general, have two major disadvantages:

1. Oxidation of C is often incomplete, which necessitates the use of correction factors to bring the C-value obtained close to those of combustion methods;
2. The C-values are subject to error because the presence in the soil of other oxidisable substances such as chloride, iron and manganese (Nelson and Sommers, 1986).

Nelson and Sommers (1986) suggest that many studies have shown that the Walkley-Black method provides variable recovery of organic C from soils. In some soils >90% of the organic C may be oxidised, whereas with other soils <70% of the organic C is converted to CO_2. A more detailed account of the Walkley-Black method can be found in Nelson and Sommers (1986).

4.2.2 PH

Soil pH is a measure of the activity of ionized H (H^+) in the soil solution, and is one of the most indicative measurements of the chemical properties of the soil. Whether the soil is acidic, neutral or basic has much to do with the solubility of various compounds, the relative binding of ions to exchange sites, and the activity of various microorganisms (McLean, 1986).

PH is defined as the negative logarithm of the concentration of hydrogen ions in a solution, measured in moles per litre (Briggs, 1977). A pH measurement is usually made by means of either a colorimetric or an electrometric method. The electrometric method was selected since it is a standard, more accurate method (British Standards Institute, 1975). The electrometric method involves a glass, H^+-sensing (indicator) paired with a reference electrode attached to a suitable meter (McLean, 1986).

The reading is affected by the soil:solution ratio used in preparing the sample. As the volume of the solution is increased, the sample becomes less like the soil in its field state. However, if very little solution is used, it may be difficult to obtain a contact between the electrode and the soil solution. For this reason, the most widely used ratio is that of 1 : 2.5 (by weight). Since the pH of the soil may fluctuate naturally over time, or during transport and storage, it was decided that it was meaningful to measure pH within one week of sampling. Further details of the electrometric method of pH determination are provided by McLean (1986).

4.2.3 CATION EXCHANGE CAPACITY

The best single index of potential soil fertility is its capacity to exchange cations (Pitty, 1978). The typical, reverse cation exchange reaction may be written as:

$$A^+ + B^+ \text{ micelle}^- = B^+ + A^+ \text{ micelle}^-$$

and

$$C^{2+} + 2B^+ \text{ micelle}^- = 2B^+ + C^{2+} (\text{micelle}^-)^2$$

where A^+ and B^+ are univalent cations, C^{2+} is a divalent cation, and a micelle is a negatively charged colloidal soil particle, usually of clay or humus, or more commonly of both (Pitty, 1978). The cation exchange capacity (CEC) is an expression of the number of cation adsorption sites per unit weight of soil. It can be defined as the sum total of exchangeable cations that a soil can adsorb. CEC is expressed in milliequivalents per 100 grams of soil (Steila and Pond, 1989).

In all but the most acid or alkaline of soils, the major cations are Ca^{2+}, Mg^{2+}, K^+ and Na^+ in roughly proportions of 80% Ca : 15% Mg : 5% (Na + K), with variable amounts of NH_4^+, depending on the efficiency of microbial nitrification (White, 1979).

Ten soil samples were sent to the Department of Soil and Agricultural Water Science (University of Stellenbosch) for analysis. The samples were analyzed for the individual cations of calcium, magnesium, sodium and potassium as well as the CEC. The method used for determination was the ammonium acetate method which has been described in detail by Buys (1980).

4.3 DATA ANALYSIS AND REPRESENTATION

4.3.1 DESCRIPTIVE STATISTICS

The STATGRAPHICS computer programme (Statgraphics, 1989) was adopted to perform the descriptive statistical analysis. The mean, variance, range and median values of each factor influencing soil erodibility is presented in Tables 5.1 - 5.3.

4.3.2 ANALYSIS OF VARIANCE

To statistically determine whether the differences in factors controlling soil erodibility are greater between the four sample sites than within the sample sites, the Analysis of Variance test was adopted. Analysis of Variance, the F-ratio test, is the standard parametric test of difference between three or more samples (Ebdon,1985). ANOVA,an acronym for ANalysis Of VAriance, is used on interval data when more than two sample means are to be compared for difference. The null hypothesis of ANOVA is that the samples are taken from a common, normally distributed population. The alternate hypothesis is that the samples are taken from different populations. If the samples are from a common, normally distributed population (null hypothesis), it is reasonable to expect the variation within samples to be approximately equal to the variation between the samples, since both are reflections of the overall variation in the population. Any difference in these two measures of variation is merely due to chance in the sampling process. Variations between samples in this case would therefore be a reflection of the difference between populations (Ebdon, 1985).

The resulting statistic, the F-ratio, determines the ratio between the variability occurring between the sample groups and the variability occurring within each of the sample groups (Clark and Hosking, 1986). The higher the F-ratio, the greater is the likelihood that the samples represent different populations; a high F-ratio therefore represents a great deal of between-group variability and little within-group variability (the sample distributions show little overlap). A low F-ratio indicates that there is little between-group variability in relation to the amount of within-group variability occurring (the sample distributions show a great deal of overlap)(Sprinthall, 1987).

Sprinthall (1987) lists five basic assumptions that must be satisfied before an ANOVA can be performed:

1. The sample groups must be randomly and independently selected;
2. There is a normal distribution in the population from which the samples were selected;
3. The data are in interval form;
4. The within-group variances of the samples should be fairly similar. This is termed homogeneity of variance and means that ANOVA demands sample groups that do not differ too much with regard to their internal variabilities;
5. Additivity (that is the effects of Factor A (soil factor) and error on the value of X are assumed to be additive.

To ensure that the criteria for the Analysis of Variance were satisfied, the data included in the thesis were evaluated in terms of Sprinthall's assumptions:

1. The sample groups were randomly and independently selected using random number tables and a grid system;
2. The frequency distributions of the data were determined using normal probability plots (Appendix C). Based on these indices it was ascertained that the distributions of the organic carbon and infiltration rate data were skewed. Various transformations of this data were attempted (Appendix C):

   (i) LOG (X)

   (ii) SQUARE ROOT (X)

   (iii) LOG (X+1)

   Since the means of the data were positively correlated with the variances (Organic Carbon $r = 0.97$;Infiltration Rate $r = 0.90$), the logarithmic transformation was mostly likely to remedy the situation (Sokal and Rohlf, 1981). However, only 4 data points were included in the correlation and thus the coefficients must be viewed with caution. The transformations using LOG (X) therefore resulted in the least skewed distributions and therefore LOG (Organic Carbon) and LOG (Infiltration Rate) data were used for the ANOVA;
3. The data used were in interval form;
4. In order to determine whether the within group variances of the sample groups were fairly similar, Bartlett's test for homogeneity of variances was performed. It is

important to satisfy the assumption of homogeneity of variances, since if it is not met, the validity of the test is reduced (Till, 1974). However, Scheffé (1959) suggests that the assumption of homogeneity of variances can be relaxed if the groups are equal in size. For unequal groups, only moderate departures are tolerable. Bartlett's test was chosen since it is the most frequently used test and none of the alternatives (for example, Hartley's (1950) Fmax-test) are generally accepted (Clark and Hosking, 1986). However, Bartlett's test for homogeneity of variances is unduly sensitive to departures from normality and a Bartlett's P-value of less than 0.05 may indicate non-normality rather than heteroscedasticity (inequality of variances among samples)(Sokal and Rohlf, 1981). For this reason, Bartlett's test was performed on the logarithmic transformation of the organic carbon and infiltration rate data. Based on the results of the Bartlett's test, it was decided that the assumption of homoscedasticity was generally satisfied, although in certain cases, for example, the soil moisture and shear strength data, the results of the ANOVA would have to be viewed with caution. However, Williams (1986) states that small inequalities in the variances of different groups are not serious. It is when individual variances differ markedly that it is unsafe to use ANOVA.

5. The assumption of additivity has been satisfied since the Factor A (soil factor) acts independently of the unexamined factors and chance causes that are collectively referred to as error. No interaction occurs.

4.3.3 SCHEFFÉ'S RANGE TEST

Although a significant F-ratio tells us that there are significant differences among the several group means, it does not specify precisely where those differences are occurring. For this analysis, Scheffés Range test is used since it was considered by Clarke and Hosking (1986) to be the most conservative test available for determining exactly where the sample differences occur. One of the real advantages of the Scheffés Range test is that it finds significant differences between pairs **only** if the F-ratio is statistically significant. Scheffés Range test was therefore used to determine exactly where the differences between the four sample sites occurred (Tables 5.7 - 5.9). Both the ANOVA and the Scheffé's Range tests were performed using the STATGRAPHICS computer program (Statgraphics, 1989).

The analysis of variance model assumes that the soil variables are linearly independent to enable their individual contributions can be assessed (Clark and Hosking, 1986). However, within the soil variables analysed there can often be a large degree of dependence as can be seen through their intercorrelations. A situation of multicollinearity thus exists and it is for this reason that a multi-factor analysis was not attempted.

4.3.4 CORRELATION ANALYSIS

The purpose of correlation analysis is to measure the intensity of association observed between any pair of variables and to test whether it is greater than could be expected by chance alone (Sokal and Rohlf, 1981). The correlation analysis employed focused on bivariate relationships. The simple linear correlation coefficients (r values) therefore range from -1.0 (perfect negative correlation) to +1.0 (perfect positive correlation). Thus, the more the value of r deviates from zero, the greater its predictive accuracy (Sprinthall, 1987).

Coefficients of determination (r^2 values) were calculated in order to provide information about a given correlation's predictive accuracy. By multiplying r^2 by 100, the approximate percentage of information about one variable that is supplied by the other variable, can be determined (Clark and Hosking, 1986).

Correlation matrices were compiled using the STATGRAPHICS program (Statgraphics, 1989). These matrices indicated correlation coefficients (r), coefficients of determination (r^2), the number of data points used and the significance of the correlations (Appendix E).

CHAPTER 5

DISCUSSION OF THE VARIATION IN FACTORS CONTROLLING SOIL ERODIBILITY BETWEEN SAMPLE SITES

In Chapter 5 the factors influencing erodibility are analyzed to gain an understanding of the variation between groups (traffic area adjacent to pineapple lands, pineapple ridges, pineapple furrows and undisturbed soil under natural vegetation). The implications of these variations in terms of erodibility are also discussed in this chapter.

5.1 VARIATIONS BETWEEN SAMPLE SITES

The mean, variance, range and median values were the statistics selected to describe the data. The mean gives the average value of each soil characteristic influencing erodibility, while the variance and range are both measures of variability of the data. The median is an important measure of central locality since if the mean and the median values coincide, the data is considered to be symmetrical. That is, the data is normally distributed (Freund, 1974). The techniques selected to measure each of the factors controlling soil erodibility are outlined in Chapter 4. The descriptive statistics are presented in Tables 5.1 to 5.3.

TABLE 5.1: Statistics describing factors influencing soil erodibility in the Glenrosa and Oakleaf soil forms

SOIL CHARACTERISTIC	TRAFFIC AREA	PINE. RIDGE	PINE. FURROW	NATURAL VEGET.
SOIL MOISTURE (% weight)	9.018 6.007 (13.74) 9.44	8.989 7.890 (18.51) 9.08	12.803 6.124 (16.35) 12.48	10.004 22.233 (27.61) 9.36
BULK DENSITY ($g.cm^{-3}$)	1.659 0.034 (0.99) 1.66	1.394 0.020 (0.66) 1.39	1.579 0.024 (0.88) 1.59	1.322 0.692 (1.30) 1.38
POROSITY (% volume)	32.562 51.584 (38.88) 31.96	41.297 34.804 (28.38) 42.33	34.855 40.941 (27.08) 34.90	42.971 65.932 (42.87) 42.21
INFILTRATION RATE ($ml.minute^{-1}$)	38.732 77.369 (32.85) 37.39	331.130 15558.9 (579.71) 333.33	70.612 634.583 (124.42) 65.28	648.111 330017.0 (1909.09) 503.51
AGGREGATE STABILITY (% volume)	82.320 45.421 (26.92) 81.05	85.463 27.368 (23.07) 86.35	85.651 35.847 (30.05) 86.16	94.628 12.006 (19.23) 95.50
SHEAR STRENGTH (KPa)	66.15 622.197 (98.00) 60.00	18.700 70.790 (39.00) 17.00	31.033 201.66 (59.00) 27.00	42.117 268.45 (84.00) 44.00
SAND (%)	76.433 21.771 (15.00) 75.50	74.133 20.671 (14.00) 73.50	76.200 11.338 (16.00) 77.00	84.033 16.033 (17.00) 82.50
SILT (%)	7.333 9.264 (9.00) 7.00	8.733 5.100 (10.00) 9.50	7.700 8.907 (10.00) 7.00	8.600 11.766 (12.00) 10.00
CLAY (%)	16.300 5.045 (10.00) 16.00	17.133 9.085 (10.00) 18.00	16.200 5.200 (9.00) 16.00	7.367 3.620 (8.00) 7.00
ORGANIC CARBON (%)	0.593 0.044 (0.92) 0.59	0.661 0.057 (0.75) 0.80	0.567 0.028 (0.63) 0.55	1.677 0.806 (4.20) 1.49
PH (pH units)	3.971 0.209 (2.35) 3.99	3.674 0.135 (1.51) 3.54	3.587 0.200 (3.16) 3.54	5.064 0.280 (2.45) 5.00

where 9.018 = mean

6.007 = variance

(13.74) = (range)

9.44 = median

TABLE 5.2: Statistics describing factors influencing soil erodibility in the Glenrosa soil form

SOIL CHARACTERISTIC	TRAFFIC AREA	PINE. RIDGE	PINE. FURROW	NATURAL VEGET.
SOIL MOISTURE (% weight)	7.260 **3.469** (9.53) 6.77	10.254 **6.972** (15.00) 9.76	13.387 **8.640** (13.31) 12.85	11.584 **21.990** (25.94) 10.56
BULK DENSITY ($g.cm^{-3}$)	1.722 **0.033** (0.99) 1.69	1.456 **0.015** (0.50) 1.45	1.616 **0.022** (0.77) 1.61	1.481 **0.032** (0.90) 1.48
POROSITY (% volume)	30.740 **63.733** (38.88) 30.71	39.609 **19.003** (17.49) 40.16	33.043 **33.674** (20.57) 32.48	38.648 **37.846** (30.60) 38.42
INFILTRATION RATE ($ml.minute^{-1}$)	42.228 **100.600** (26.33) 41.60	351.978 **4115.610** (199.80) 336.16	67.915 **145.673** (40.20) 65.28	520.936 **309332** (1909.1) 365.07
AGGREGATE STABILITY (% volume)	78.728 **27.728** (23.63) 78.49	83.742 **28.902** (18.22) 84.09	83.860 **45.221** (27.08) 85.54	93.826 **9.713** (14.16) 93.88
SHEAR STRENGTH (KPa)	71.300 **533.39** (92.00) 68.00	16.433 **39.840** (27.00) 15.50	22.200 **38.717** (28.00) 23.00	43.733 **188.064** (54.00) 45.50
SAND (%)	80.667 **4.095** (8.00) 80.00	78.133 **6.981** (7.00) 78.00	77.400 **8.400** (11.00) 77.00	86.867 **11.981** (14.00) 87.00
SILT (%)	4.533 **0.695** (3.00) 5.00	7.333 **4.952** (8.00) 8.00	5.800 **5.743** (10.00) 5.00	6.067 **9.067** (9.00) 5.00
CLAY (%)	14.800 **3.743** (7.00) 15.00	14.533 **3.124** (6.00) 15.00	16.933 **6.924** (9.00) 17.00	7.067 **4.210** (8.00) 7.00
ORGANIC CARBON (%)	0.439 **0.013** (0.45) 0.41	0.490 **0.054** (0.75) 0.39	0.488 **0.031** (0.62) 0.44	1.203 **0.348** (2.39) 1.26
PH (pH units)	3.718 **0.222** (2.35) 3.55	3.413 **0.043** (1.15) 3.35	3.288 **0.081** (1.5) 3.35	5.057 **0.485** (2.45) 5.00

where 7.260 = mean

3.469 = variance

(9.53) = (range)

6.77 = median

TABLE 5.3: Statistics describing factors influencing soil erodibility in the Oakleaf soil form

SOIL CHARACTERISTICS	TRAFFIC AREA	PINE. RIDGE	PINE. FURROW	NATURAL VEGET.
SOIL MOISTURE (% weight)	10.777 **2.356** (12.22) 10.71	7.725 **5.690** (10.71) 7.88	12.218 **3.016** (9.77) 12.41	8.424 **17.776** (14.25) 6.93
BULK DENSITY ($g.cm^{-3}$)	1.595 **0.028** (0.82) 1.60	1.332 **0.017** (0.61) 1.32	1.541 **0.023** (0.60) 1.56	1.162 **0.056** (1.10) 1.18
POROSITY (% volume)	34.384 **34.346** (24.45) 33.26	42.985 **45.908** (28.38) 44.00	36.666 **42.831** (27.08) 37.07	47.293 **57.633** (33.11) 46.58
INFILTRATION RATE ($ml.minute^{-1}$)	35.235 **35.567** (18.92) 36.37	310.283 **27765.10** (579.71) 303.85	73.309 **1177.840** (124.42) 64.59	775.284 **426391.O** (1727.3) 761.91
AGGREGATE STABILITY (% volume)	85.912 **37.982** (25.19) 85.54	87.183 **20.655** (18.73) 87.94	87.442 **21.074** (21.96) 87.88	95.430 **13.382** (19.23) 96.52
SHEAR STRENGTH (Kpa)	61.000 **677.586** (98.00) 53.00	20.967 **93.551** (37.00) 20.50	39.867 **210.120** (45.00) 40.00	40.500 **352.879** (84.00) 37.50
SAND (%)	72.200 **2.600** (4.00) 73.00	70.133 **1.552** (4.00) 70.00	75.000 **12.000** (10.00) 76.00	81.200 **4.029** (6.00) 82.00
SILT (%)	10.133 **1.695** (4.00) 10.00	10.133 **1.410** (4.00) 10.00	9.600 **4.971** (7.00) 10.00	11.133 **1.552** (4.00) 11.00
CLAY (%)	17.800 **1.886** (4.00) 18.00	19.733 **1.210** (4.00) 20.00	15.467 **2.695** (6.00) 15.00	7.667 **3.095** (5.00) 7.00
ORGANIC CARBON (%)	0.749 **0.028** (0.80) 0.73	0.833 **0.003** (0.26) 0.82	0.647 **0.014** (0.46) 0.64	2.150 **0.830** (3.44) 1.75
PH (pH units)	4.224 **0.071** (0.98) 4.25	3.934 **0.085** (1.14) 3.93	3.885 **0.142** (1.90) 3.77	5.072 **0.084** (1.27) 5.01

where 10.77 = mean

2.356 = variance

(12.22) = (range)

10.71 = median

Analysis of variance, the standard parametric test of difference between three or more samples, was used to determine whether the between-group variation was greater than the within-group variation. The requirements for the Analysis of Variance, as summarized in Chapter 4, are presented in Appendix D. The organic carbon and infiltration rate data distributions did not satisfy the assumptions of normality and thus they were transformed using a logarithmic transformation. Tables 5.4 to 5.6 illustrate the results of the Analysis of Variance. All tests were performed at the 95% confidence level. A high F-ratio represents a great deal of between-group variation compared to little within-group variability, while a lower F-ratio indicates that there is little between-group variation in relation to the amount of within-group variability.

TABLE 5.4: Results of the Analysis of Variance - Glenrosa and Oakleaf soil forms

SOIL CHARACTERISTIC	DEGREES OF FREEDOM		CONF. LEVEL	F RATIO	P VALUE	SIG. DIFF.
	B.G.	W.G.				
Soil Moisture	3	476	95	36.638	0.000	Y
Bulk Density	3	476	95	80.157	0.000	Y
Porosity	3	236	95	31.052	0.000	Y
Infiltration	3	76	95	18.476	0.000	Y
Agg. Stability	3	236	95	55.882	0.000	Y
Shear Strength	3	236	95	84.003	0.000	Y
% Sand	3	116	95	32.479	0.000	Y
% Silt	3	116	95	1.597	0.194	N
% Clay	3	116	95	111.025	0.000	Y
Organic Carbon	3	236	95	73.588	0.000	Y
pH	3	236	95	135.438	0.000	Y

where B.G. = between groups

W.G. = within groups

Y = significant difference

N = no significant difference

TABLE 5.5: Results of the Analysis of Variance - Glenrosa soil form

SOIL CHARACTERISTIC	DEGREES OF FREEDOM BG	WG	CONF. LEVEL	F RATIO	P VALUE	SIG. DIFF.
Soil Moisture	3	236	95	38.988	0.000	Y
Bulk Density	3	236	95	36.194	0.000	Y
Porosity	3	116	95	14.387	0.000	Y
Log(Infiltration)	3	36	95	55.956	0.000	Y
Agg. Stability	3	116	95	43.064	0.000	Y
Shear Strength	3	116	95	92.790	0.000	Y
% Sand	3	56	95	35.279	0.000	Y
% Silt	3	56	95	3.867	0.014	N
% Clay	3	56	95	62.025	0.000	Y
Log(Organic Carbon)	3	116	95	36.248	0.000	Y
pH	3	116	95	95.292	0.000	Y

where W.G. = within groups

B.G. = between groups

Y = significant difference

N = no significant difference

TABLE 5.6: Results of the Analysis of Variance - Oakleaf soil form

SOIL CHARACTERISTIC	DEGREES OF FREEDOM BG	WG	CONF. LEVEL	F RATIO	P VALUE	SIG. DIFF.
Soil Moisture	3	236	95	36.064	0.000	Y
Bulk Density	3	236	95	76.353	0.000	Y
Porosity	3	116	95	23.089	0.000	Y
Log(Infiltration)	3	36	95	75.746	0.000	Y
Agg. Stability	3	116	95	24.325	0.000	Y
Shear Strength	3	116	95	24.051	0.000	Y
% Sand	3	56	95	68.804	0.000	Y
% Silt	3	56	95	2.555	0.064	N
% Clay	3	56	95	189.358	0.000	Y
Log(Organic Carbon)	3	116	95	128.084	0.000	Y
pH	3	116	95	94.732	0.000	Y

where W.G. = within groups

B.G. = between groups

Y = significant difference

N = no significant difference

Although a significant F-ratio represents significant differences between the traffic area, pineapple ridge, pineapple furrow and natural vegetation group means, it does not specify where the differences between groups are occurring. The direction of the differences is indicated by Scheffé's Range test, presented in Tables 5.7 to 5.9. Scheffé's Range test combines similar groups together and allows homogenous groups to be considered as single entities. That is, if large enough differences occur between the mean values of soil variables between the traffic area, pineapple ridges and furrows and natural vegetation, they will be considered as separate groups. However, if the differences between the mean values of the soil characteristic are small, the four sample sites will be combined into a single group.

TABLE 5.7: Results of the Scheffé's Analysis - Glenrosa and Oakleaf soil forms

SOIL CHARACTERISTIC	SCHEFFÉ'S HOMOGENOUS GROUPINGS
Soil Moisture	TRV F
Bulk Density	T R F V
Porosity	TF RV
Log(Infiltration Rate)	T RV F
Aggregate Stability	T RF V
Shear Strength	T R F V
% Sand	TRF V
% Silt	TRFV
% Clay	TRF V
Log(Organic Carbon)	TRF V
pH	T RF V

where T = traffic area

R = pineapple ridge

F = pineapple furrow

V = undisturbed soil under natural vegetation

TABLE 5.8: Results of the Scheffé's Analysis - Glenrosa soil form

SOIL CHARACTERISTIC	SCHEFFÉ'S HOMOGENOUS GROUPINGS
Soil Moisture	T RV F
Bulk Density	T RV F
Porosity	TF RV
Log(Infiltration Rate)	TF RV
Aggregate Stability	T RF V
Shear Strength	T RF V
% Sand	TR RF V
% Silt	TFV RFV
% Clay	TR TF V
Log(Organic Carbon)	TRF V
pH	TR RF V

where T = traffic area

R = pineapple ridge

F = pineapple furrow

V = undisturbed soil under natural vegetation

TABLE 5.9: Results of the Scheffé's Analysis - Oakleaf soil form

SOIL CHARACTERISTIC	SCHEFFÉ'S HOMOGENOUS GROUPINGS
Soil Moisture	T RV F
Bulk Density	TF R V
Porosity	TF RV
Log(Infiltration Rate)	T R F V
Aggregate Stability	TRF V
Shear Strength	T R FV
% Sand	TR F V
% Silt	TRFV
% Clay	T R F V
Log(Organic Carbon)	TR TF V
pH	T RF V

where T = traffic area

R = pineapple ridge

F = pineapple furrow

V = undisturbed soil under natural vegetation

The correlation matrices, measuring the intensity of association observed between any pair of soil variables controlling erodibility, are presented in Appendix E. Table 5.10 illustrates the lowest r values which are significant at the 95% confidence level for each sample size. For example, if N = 480, any r value above 0.15 is significant at the 95% level.

TABLE 5.10: The relationship between sample size and the lowest r values significant at the 95% level

SAMPLE SIZE	SIGNIFICANT R VALUE
480	0.150
240	0.200
120	0.250
80	0.300
60	0.350
40	0.400

5.1.1 SOIL MOISTURE

The percentage soil moisture (determined by the gravimetric method) was greater in the furrows of the pineapple lands (mean - 12.80%) than in the natural vegetation (mean - 10.00%), traffic area (mean - 9.02%) and pineapple ridge (mean - 8.99%)(in the combined (Glenrosa and Oakleaf) data set). The Glenrosa soil form generally had a higher percentage soil moisture than the Oakleaf soil form. This difference cannot be ascribed to the antecedent soil moisture conditions since the Glenrosa soil form received a total of 5.3mm of rainfall in the two week period preceding sampling, while the Oakleaf soil form received a total of 18.6mm of rain in the two weeks before sampling. This difference can also not be ascribed to differences in slope aspect since the Glenrosa soil form was NE facing, therefore receiving more sunlight and possibly resulting in higher evaporation rates on these slopes. The results of the Analysis of Variance indicate a significant difference in soil moisture between the four sample groups. However, these results must be viewed with some caution since one of the assumptions of the test (homogeneity of variances) was not satisfied (the assumptions of Analysis of Variance are outlined in Chapter 4). The Scheffé's Range test combined the traffic-ridge-vegetation / furrow groups (combined data set) or the traffic / ridge-vegetation / furrow groups (Glenrosa and Oakleaf soil forms).

The moisture percentage was therefore greatest in the furrow. This may be due to the shape of the pineapple leaves and the fact that these leaves are very effective at channelling and concentrating water to the furrow. Another possible reason for a higher soil moisture in the furrow is the lack of vegetation, and therefore evapotranspiration in the furrow. Evaporation is also reduced due to the shading effect of the leaves. The fact that clay content is higher in the furrow relative to the natural vegetation suggests that the higher soil moisture values in this area are due to the increased water-holding capacity of clay. The lower surface soil moisture values found in the ridges may be due to the loosening of the soil in the ridges, causing infiltration rates to be increased. The traffic area also demonstrated a relatively low mean soil moisture percentage. This is probably a consequence of compaction reducing infiltration and causing surface runoff.

The following extract from Appendix E indicates no strong correlations (r values) between soil moisture and any other variables influencing soil erodibility.

	BD	P	IR	AS	SS	%SA	%SI	%C	OC	PH
SM	-0.088	0.155	-0.097	0.214	-0.098	0.153	0.018	-0.183	0.104	0.206

5.1.2 BULK DENSITY

Dry bulk density (determined by the gravimetric method) was higher in the traffic area and pineapple furrow than in the pineapple ridges and natural vegetation (mean values of 1.66 and 1.58 $g.cm^{-3}$ versus 1.39 and 1.32 $g.cm^{-3}$ respectively in the combined data set). This trend was noted in both the Glenrosa and Oakleaf soil forms. The results of the Analysis of Variance indicated significant bulk density differences between the four sample groups in all cases. Using the combined data base (both the Glenrosa and the Oakleaf soil forms), the Scheffé grouping separated out all four sample groups. Each sample site was sufficiently homogenous to be considered as a single entity. That is, large enough differences in bulk density occurred between the traffic area, pineapple ridges and furrows and the natural vegetation for them to be considered separate groups. However, in the Glenrosa soil form, the ridge and the natural vegetation sites were grouped together. While very different processes contribute to their lower bulk densities (loosening-up versus undisturbed biological activity), their bulk densities are much lower than those in the pineapple furrows and traffic sites and thus they were grouped together. In the Oakleaf soil form, the traffic and furrow sites were combined by Scheffé's homogenous groupings.

These results illustrate the consequence of compaction reducing the porosity of the soil and resulting in increased bulk density. These trends can therefore be explained in terms of vehicular and foot compaction in the traffic and furrow regions. Compaction involves the rearrangement and movement of solid particles closer together. Fine grains are forced into the voids between coarse grains, thus increasing bulk density (Smith, 1990). These results are in agreement with recent research on bulk density changes following cultivation (Voorhees and Lindstrom, 1984; Borchert, 1988). The lower bulk densities in the ridge area can be attributed to the loosening-up process which accompanies ridging and cultivation. This ridging process results in some rearrangement and breakup of the aggregates, which causes an opening up of the pore spaces and fissures. This is why the ridged area of cultivated soils tends to be looser and less dense than that of untilled virgin soils (Ross, 1989). The lower bulk density in the natural vegetation can be ascribed to the higher organic matter contents that occur in those soils.

	SM	P	IR	AS	SS	%SA	%SI	%C	OC	PH
BD	-0.088	-0.903	-0.565	-0.460	0.217	0.010	-0.465	0.289	-0.652	-0.460

According to the above extract from the correlation matrices (Appendix E), bulk density is significantly correlated with porosity (r = -0.903) (Figure 5.1). Since porosity is determined from bulk density measurements, these variables are considered to be interdependent (Steila and Pond, 1989). These results are in accordance with a study reported by Foth (1978) in which long-term cultivation resulted in a significant decrease in total pore space and a paralleled increase in bulk density.

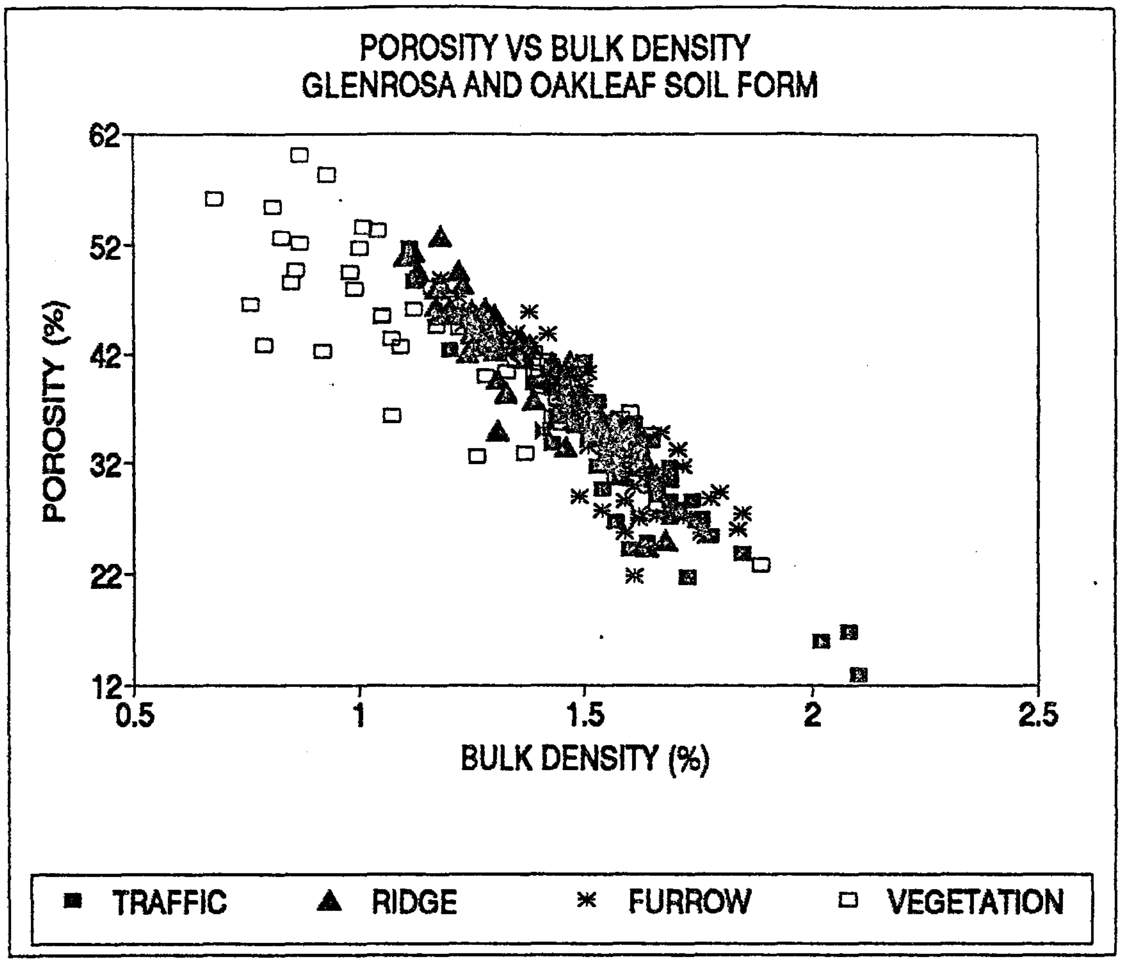


FIGURE 5.1: Scatterplot showing the relationship between porosity and bulk density for the four study sites

Bulk density is also correlated with the percentage organic carbon in both the combined data set and the Oakleaf soil form data (r = -0.652 and -0.680 respectively). The reason for this relationship is the fact that organic matter has a considerably lower density than other minerals making up the soil (0.4 $g.cm^{-1}$ compared to 2.65 $g.cm^{-1}$) (Briggs, 1977). Increased organic content will thus result in a lower bulk density of the soil. Organic matter is therefore an important factor affecting bulk density, particularly in uncultivated soils (Pitty, 1978). Even in arable and grassland soils, 50 per cent of the variation in bulk density can be accounted for by variations in the organic content of the soil (Williams, 1971). Figure 5.2 illustrates that while no relationship exists between bulk density and organic carbon in the pineapple lands, a weak inverse relationship exists in the areas under natural vegetation. This data suggests that whilst bulk density appears to be influenced by organic carbon under natural vegetation, some other factor controls the bulk density of soils under pineapples. The higher values in the traffic areas and furrows as opposed to the ridges suggest that compaction in the furrows and road and tillage in the ridges may be the controlling factors.

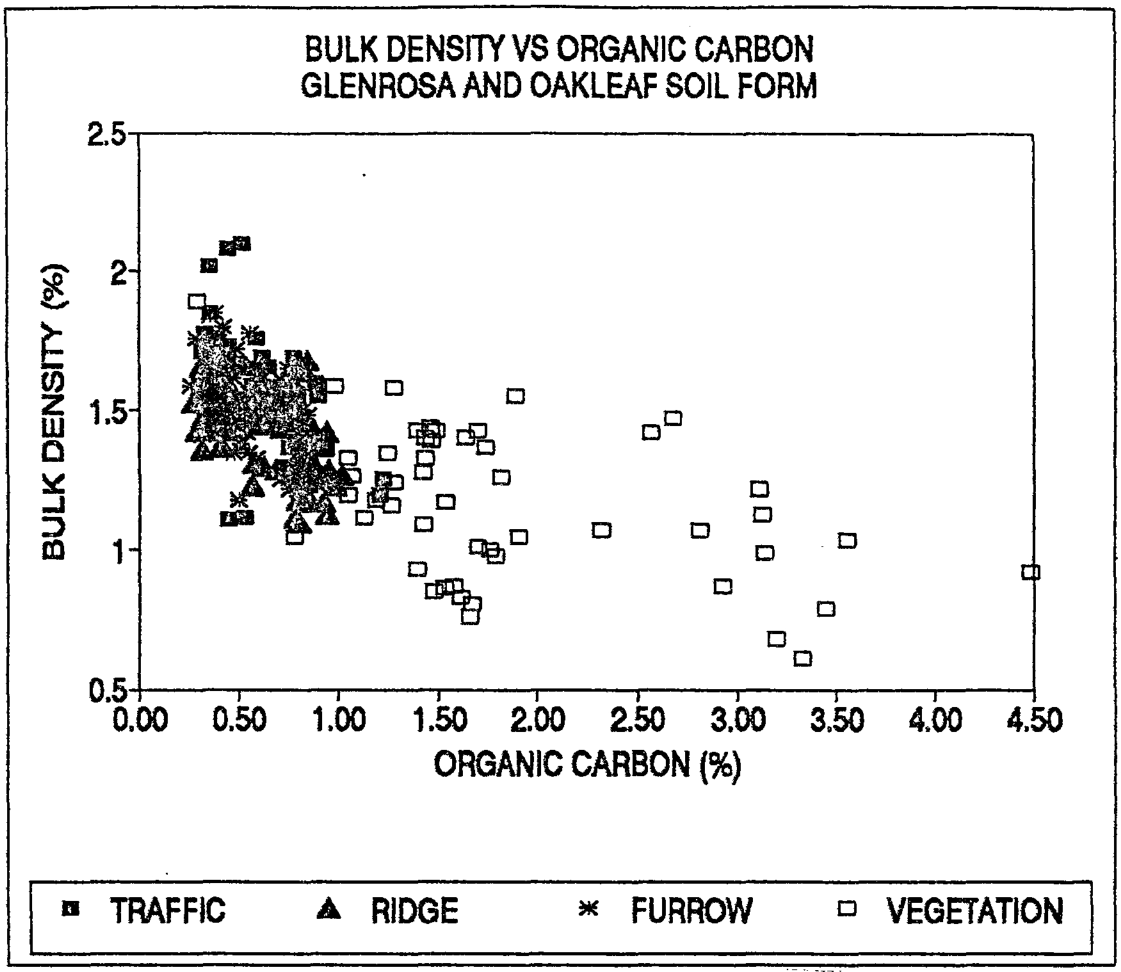


FIGURE 5.2: Scatterplot showing the relationship between bulk density and organic carbon for the four study sites

While other correlations contributed to an understanding of the interrelationships between bulk density and additional factors influencing soil erodibility, they are too weak to be considered meaningful. An example of this situation is the inverse relationship between bulk density and infiltration rate (r = -0.565), which is considered to be significant since it is above r = ±0.30 (N = 80) (Table 5.10) , but not meaningful since the correlation is too weak.

5.1.3 POROSITY

Porosity was not measured directly, but was calculated from the values for bulk density and particle density (determined by the pycnometric method). Since bulk density and porosity are considered to be interdependent variables (Pitty, 1978), the porosity results showed similar trends to those observed for bulk density.

In all data sets, porosity was lower in the traffic (mean - 32.56%) and furrow (mean - 34.86%) sites compared to the ridge (mean - 41.30%) and natural vegetation (mean - 42.97%) sites. The results of the ANOVA test conducted on the porosity again exhibited a significant difference in porosity for the four sample sites. In all data bases, Scheffé's homogenous groupings resulted in a combination of the traffic-furrow and ridge-natural vegetation sites. This is a similar situation to that found in the bulk density groupings, but not exactly the same due to the differences afforded by particle density variations. Particle densities varied from 1.93 to 2.56 $g.cm^{-3}$ in the Glenrosa soil form and 1.38 to 2.50 $g.cm^{-3}$ in the Oakleaf soil from. The wide ranges encountered were possibly due to the fact that a volumetric flask was used instead of a pycnometer in the measurement of particle density. This was because of the large number of samples that had to be analyzed and the shortages of pycnometers. Hence, slight inaccuracies resulted. However, the mean particle density was 2.38 and 2.19 $g.cm^{-3}$ for the Glenrosa and Oakleaf soil forms respectively.

The lower porosity values in the traffic and furrow are again a consequence of vehicular and foot compaction leading to aggregate destruction, increased bulk densities and reduced porosities in the traffic and pineapple furrow sites. These results agree with Campbell, Dickson and Ball (1982) who discovered that air-filled porosity decreased by over 50% due to compaction by a single wheel pass. High porosity values (as demonstrated on the ridge) and low bulk density values are associated with recently cultivated topsoils in which abundant pore spaces exist both within and between the aggregates (Briggs, 1977). The porosity is highest in those soils under natural vegetation which will result in increased water infiltration in this area.

According to the following extract from the correlation analyses (Appendix E), porosity was only notably related to bulk density. R was equal to -0.903 in the combined data base, -0.941 in the Glenrosa soil form data and -0.881 in the Oakleaf soil form data.

	SM	BD	IR	AS	SS	%SA	%SI	%C	OC	PH
P	0.155	-0.903	0.444	0.330	-0.261	0.012	0.282	-0.204	0.473	0.382

5.1.4 INFILTRATION RATE

The mean infiltration rate, as determined by the single ring infiltrometer method, was greater in the natural vegetation (648 $ml.minute^{-1}$) compared to the traffic area (39 $ml.minute^{-1}$), pineapple ridge (331 $ml.minute^{-1}$) and the pineapple furrow (71 $ml.minute^{-1)}$. Very similar trends occurred in both the Glenrosa and Oakleaf soil forms. An extremely wide range of infiltration rates was found in the soils of the natural vegetation (1910 $ml.minute^{-1}$), probably due to the non-uniformity of biological activity. Examples of the heterogeneity of biological activity include different vegetation types as well as paths and animal tracks that occur.

Appendix D (Requirements for using Analysis of Variance) indicates that the infiltration rate data did not satisfy the assumptions of normality and homogeneity of variances. The infiltration rate data were therefore transformed using a logarithmic transformation. The results of the Analysis of Variance demonstrate a significant difference in log(infiltration rates) between the four sample sites. The Scheffé's homogenous grouping combined the ridge-vegetation sites in the combined data base, the traffic-furrow in the Glenrosa soil form and permitted each of the four sites to remain a single entity in the Oakleaf soil form.

The slower rate of infiltration in the traffic area and pineapple furrow is likely to be due to compaction and reduced porosity as a result of foot and vehicular traffic. These results correspond to those of Elliot (1984) who demonstrated that cultivation resulted in a reduction in the total macropore space, leading to a lower rate of infiltration.

The ridging process, through the loosening-up process, increases the infiltration rate. Since the infiltration capacity may determines runoff and therefore the likelihood of erosion, Ross (1989) states that the potential for erosion will be lowest immediately after tillage (ridging) and soil disturbance, increasing through time with the development of surface crusting or compaction.

The infiltration rate is higher in the natural vegetation as a result of the higher organic content, better developed structure and lower bulk density in these soils as compared to the soils under the pineapple lands. These results compare favourably with the findings of

Gifford and Hawkins (1978) who demonstrated that infiltration rates are generally higher on grasslands than on arable land.

The extract from the correlation matrix of the combined data set (Appendix E) indicated no notable correlations between infiltration rates and other soil erodibility controlling factors.

	SM	BD	P	AS	SS	%SA	%SI	%C	OC	PH
IR	-0.097	-0.565	0.253	0.399	-0.071	0.253	0.242	-0.463	0.589	0.423

The only outstanding correlations between infiltration rate and other factors influencing soil erodibility that occurred, were in the Oakleaf soil form. The following correlations were deemed noteworthy:

Infiltration Rate and Bulk Density $r = -0.631$

Organic Carbon $r = 0.680$

Both a decrease in bulk density and an increase in organic carbon would loosen-up the soil, resulting in an increased infiltration capacity. Another relatively high correlation was that between infiltration rate and percentage clay ($r = -0.604$). A possible reason for this result is that soils with swelling clays do not maintain their pore spaces well and therefore decrease infiltration rate (Morgan, 1986). Another conceivable reason given by Levy et al. (1986) is that the movement of clay into the upper soil regions clog up the conductivity pores and reduce infiltration rates. This would explain the slow infiltration rates in the furrows, since the B horizon (zone of accumulation of clays) may be exposed in places.

5.1.5 AGGREGATE STABILITY

Aggregate stability was determined by observing the change in volume of the soil on 30 minute immersion in water. The mean aggregate stability of the natural vegetation (94.63%) was higher than that occurring in the pineapple lands (traffic - 82.32%; ridge - 85.46%; furrow - 85.65%). A wider range of aggregate stability values occurred in the soils of the pineapple lands compared to the soils of the natural vegetation.

The Analysis of Variance test demonstrated a significant difference in aggregate stability values between the four sample sites. The direction of the difference was determined using a Scheffé's Range test. In both the combined data base as well as the Glenrosa soil form data, the ridge-furrow sites are combined, whereas in the Oakleaf soil form, the pineapple lands (traffic-ridge-furrow) are separated from the natural vegetation.

These results show similar trends to those discovered by Low (1955; 1972) and Dettman (1959). The reasons for the lower aggregate stability in the traffic and furrow areas are the mechanical agricultural practices that break down the structure and compact the soil in these areas, resulting in a reduced aggregate stability. The aggregates in the ridge soil are also less stable than those under natural vegetation, since the process of ridging actually breaks up the soil aggregates, reducing their stability. Another factor resulting in a reduced aggregate stability in the pineapple lands is the lower organic content that occurs in this area compared to the natural vegetation. The aggregation of soils is largely due to the chemical forces between colloids. Since humus has a well developed surface charge, it contributes to the process of aggregation. Powers and Skidmore (1984) demonstrated that the organic bonds between aggregates are broken up by mechanical disruption. Since these bonds are responsible for aggregate stability, disturbed soils under cultivation showed poorer aggregate stabilities than uncultivated soils.

The extract from the correlation matrix of the combined data set illustrates the relationships between aggregate stability and other factors influencing erodibility. None of these correlations were particularly noteworthy since all factors influencing erodibility were poorly correlated with aggregate stability in the combined data set.

	SM	BD	P	IR	SS	%SA	%SI	%C	OC	PH
AS	0.214	-0.460	0.330	0.399	-0.057	0.260	0.322	-0.508	0.534	0.606

In the Oakleaf soil form, however, a meaningful correlation occurred between aggregate stability and percentage organic carbon ($r = -0.652$) (Figure 5.3). The r^2 value of 0.425 implies that 42.5% of the variation in aggregate stability can be explained by the variation in organic carbon. This is because the increased organic matter increases cohesiveness and therefore the stability of the peds (Morgan, 1986). Organic matter is therefore an important aggregate cementing agent (Bryan, 1968).

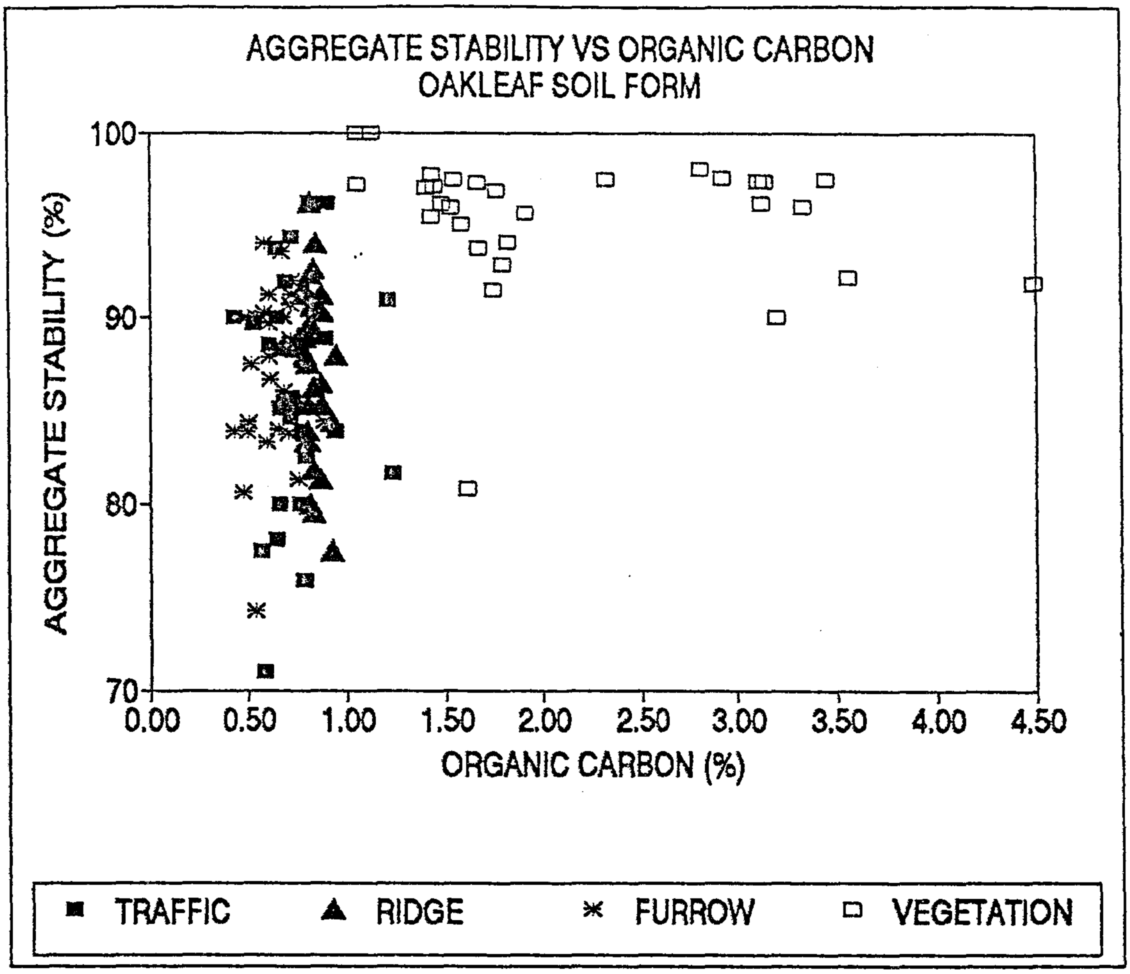


FIGURE 5.3: Scatterplot showing the relationship between aggregate stability and organic carbon for the four study sites

However, weak relationships occur between aggregate stability and pH (r = 0.606) and percentage clay (r = -0.508) in the combined data set (Figure 5.4). A possible reason for the correlation between aggregate stability and pH is that at increased pH values, calcium (a chemical binder in sandy soils) availability increases. All divalent cations (calcium) are held more firmly by colloids than monovalent cations (Evans, 1980). The inverse correlation between aggregate stability and percentage clay appears to be spurious since one would expect a direct relationship to occur since clay is considered to be a 'binder' increasing cohesiveness and aggregate stability (Pitty, 1978). However, Gerard (1981) states that disruptive forces occurring in aggregates on wetting can be attributed to the swelling of oriented clay and to the compression of trapped air. The occurrence of swelling clays may therefore be a possible reason for the inverse correlation between aggregate stability and clay content.

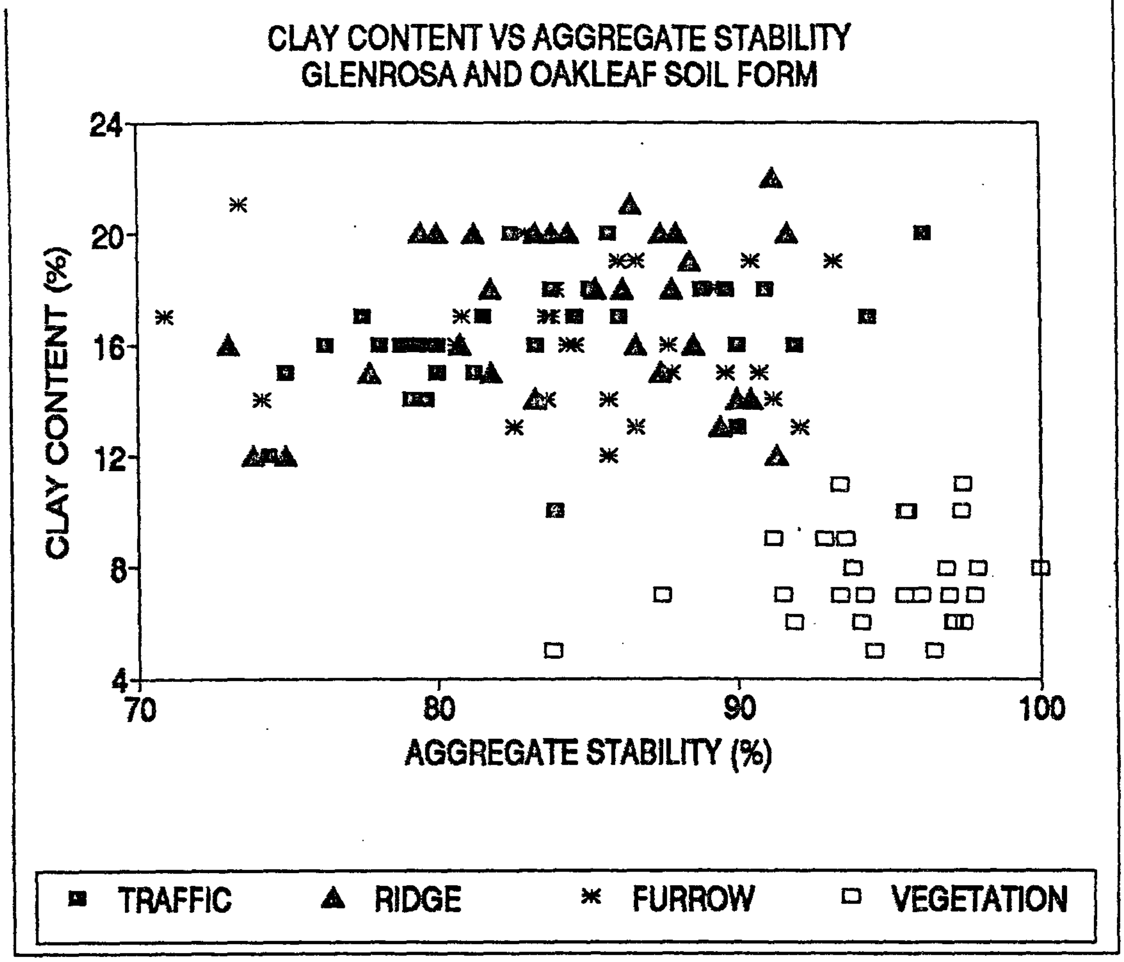


FIGURE 5.4: Scatterplot showing the relationship between clay content and aggregate stability for the four study sites

5.1.6 SHEAR STRENGTH

Shear strength was determined using a shear vane as described by the British Standards Institution (1975). The mean shear strength of the soil in the traffic area (66.15 Kpa) was greater than that of the soil in the natural vegetation (42.12Kpa), pineapple furrow (31.03Kpa) and the pineapple ridge (18.70Kpa). Again, a wide range of values occurred in the natural vegetation, but the traffic area also demonstrated a large range. This is possibly because of the difference in shear strength between the soil directly beneath the vehicle wheels (highly compacted) and the soil between the two tracks (less compacted).

The results of the Analysis of Variance again indicate a significant difference in shear strength between the four sample sites. According to Scheffé's homogenous groupings, the four sample sites were sufficiently uniform to be categorized into four separate groups in the combined data set. In the Glenrosa soil form, however, the ridge-furrow sites were grouped together and in the Oakleaf soil form, the furrow-vegetation sites were combined.

Compaction of the soils in the traffic area increases the resistance of the soil to shear failure. The soils of the natural vegetation also demonstrated relatively high shear strength values because under undisturbed conditions, the soil has a high resistance to failure. The least interference occurs at this site. The shear strength is lowest in the ridge because loosening of the soil for ridging and planting results in the disaggregation of peds, and a lower resistance to failure. Root activity may also lead to a lower shear strength on the ridge.

The extract from Appendix E demonstrates that shear strength was not strongly correlated with any other soil variable influencing erodibility.

	SM	BD	P	IR	AS	%SA	%SI	%C	OC	PH
SS	-0.098	0.217	-0.261	-0.071	-0.057	0.086	-0.035	-0.079	-0.010	0.192

5.1.7 SOIL TEXTURE

In all cases, the percentage sand content was higher in the natural vegetation (mean - 84.03%). The traffic, ridge and furrow sites had mean values of 76.43, 74.15 and 74.20% respectively. The percentage sand content was slightly lower in the Oakleaf soil form as compared to the Glenrosa soil form. The results of the ANOVA statistical test demonstrated a significant difference in sand content between sample groups and Scheffé's range test separated out the natural vegetation site as having a different percentage sand content from the other three sample sites (in the combined data set).

The percentage silt content was very similar in all four sample sites. The ANOVA test indicated no significant differences in silt content between sample groups and the Scheffé's Range test united all four sites into one group (in the combined data set).

The percentage clay content was more than 50% higher in the pineapple lands (traffic mean - 16.30%; ridge mean - 17.13%; furrow mean - 16.20%) than in the natural vegetation (mean - 7.37%). The results of the ANOVA test show a significant difference in clay content between the four sample sites. Scheffé's homogenous grouping considered the percentage clay content in the natural vegetation to be sufficiently uniform to be separated from that in the pineapple lands.

The extracts from Appendix E illustrate the relationships between soil texture and other factors controlling erodibility.

	SM	BD	P	IR	AS	SS	%SA	%SI	%C	OC	PH
%SA	0.153	0.010	0.012	0.253	0.260	0.086	1.000	-0.562	-0.845	0.245	0.403
%SI	0.018	-0.465	0.282	0.242	0.322	-0.035	-0.562	1.000	0.036	0.354	0.272
%C	-0.183	0.289	-0.204	-0.463	-0.508	-0.079	-0.845	0.036	1.000	-0.521	-0.662

In all cases, the percentage of sand was highly correlated with the percentage clay content (r= -0.845 in the combined data set; r = -0.855 in the Glenrosa soil form and r = -0.941 in the Oakleaf data). Since the sum of the sand, silt and clay contents must equal 100% and the silt content remains fairly uniform, one would expect the sand and clay contents to be highly correlated. Thus as the sand content increases, the clay content decreases and *vice versa*. Clay content was inversely correlated with pH in all data sets and sand was directly to pH in the Glenrosa soil form. These correlations between soil texture and pH may be a consequence of texture determining the ability of the soil to hold and exchange nutrients (Faniran and Areola, 1978), a property of the soil which is also controlled by soil pH.. Texture and pH may thus be indirectly related.

In the Oakleaf soil form, clay content was inversely correlated with aggregate stability (r = -0.662). The impact of clay particles on aggregate stability cannot, therefore, be summarized in a simple manner since a positive relationship is mostly frequently found, but swelling clays such as montmorillonites often reduce the stability of aggregates (De Ploey and Poesen, 1985). Clay was also meaningfully related to percentage organic carbon (r = -0.670). This inverse relationship is, however, not in accordance with reported research since Birch and Friend (1956) report that a ten per cent increase in clay content appears to favour an increase in organic matter by 0.3 per cent. The relationship is, therefore, usually a positive or direct relationship. However, the relationship between clay and organic matter percentage is not easily explained beyond a given range. In vertisols on West Africa, the organic fraction starts to decline with increases in clay content beyond 35 per cent (Jones, 1973).

5.1.8 ORGANIC CARBON

Percentage organic carbon (determined by the Walkely-Black method) was almost three times greater in the natural vegetation (mean - 1.68%) than the pineapple lands (traffic mean - 0.59%; ridge mean - 0.66%; furrow mean - 0.57%). Again, a much greater range occurred in percentage organic carbon in the natural vegetation. Percentage organic carbon was also significantly higher in all four sample sites in the Oakleaf soil form than in the Glenrosa soil form.

The results of the Analysis of Variance demonstrate a significant difference in the log transformed organic carbon data between the four sample sites. Scheffé's Range test categorized the percentage organic carbon data into two groups in the combined data set (natural vegetation and traffic-ridge-furrow).

These results may be explained by a higher percentage vegetation cover in the natural vegetation where no living material is removed from the site. The slightly higher organic carbon value in the ridge (compared to the traffic and furrow areas), is probably because living material grows on the ridge. The organic matter content in the ridge is, however, reduced by the application of pesticides and herbicides. This decline in organic content after cultivation has been well documented by several authors (Briggs and Courtney, 1985; Ross, 1989 and West et al., 1991).

The relationships between organic carbon and other variables controlling soil erodibility are illustrated in the following excerpt from Appendix E:

	SM	BD	P	IR	AS	SS	%SA	%SI	%C	PH
OC	0.104	-0.652	0.473	0.589	0.534	-0.010	0.245	0.345	-0.521	0.628

Organic carbon was correlated with many soil variables influencing erodibility, such as aggregate stability but these correlations are too weak to be notable. Organic carbon was, however relatively strongly correlated with bulk density ($r = -0.652$) in the combined data set. As discussed above, organic matter is a major factor influencing bulk density (Pitty, 1978).

While no meaningful correlations occurred in the Glenrosa soil form, organic carbon was related to the following soil characteristics in the Oakleaf soil form:

Bulk Density   r = -0.680

Infiltration Rate   r = 0.652

Percentage Clay   r = -0.670

PH   r = 0.693

A likely interpretation for these results is that an increase in organic carbon will reduce the bulk density of the soil due to the lower density of organic matter. The reduction in bulk density may then result in an increased infiltration rate. Organic matter usually has a low pH value due to the humic acids in the organic matter, and the low pH of relatively undecomposed organic horizons is partly self-perpetuating (Ross, 1989). One would therefore expect an inverse relationship between organic carbon and pH. This was, however, not the case and some other factor must be causing a direct correlation between organic carbon and pH. Organic carbon is, therefore, clearly not an independent variable, but rather a function of several interrelated factors.

5.1.9 PH

PH, as determined by the electrometric method, is much higher (mean - 5.06) in the natural vegetation than in the pineapple lands. The mean values for the traffic, ridge and furrow areas were 3.97, 3.67 and 3.59 respectively. Similar trends occurred in the Glenrosa and Oakleaf soil forms.

The findings of the ANOVA test demonstrated a significant difference in pH units in the four sample sites. The results of the Scheffé's Range test grouped the ridge-furrow areas together. while leaving the traffic and natural vegetation areas as separate entities.

The increased acidity of the pineapple soils may be due to fertilization with nitrogen (300 - 450 $kg.ha^{-1}$ every two years (Purdon, 1991)) over a number of years. However, this does not explain the reduced pH in the traffic areas adjacent to these lands and therefore another process must be operating in the traffic areas to cause an increase in acidity. This process may perhaps be the fertilizers from the pineapple lands being washed onto the road during surface runoff, increasing the acidity of the area. These results are in accordance with those reported by Py et al. (1987). Since Etherington (1975) considers soils with low pH values to be indicative of cation unsaturated soils, nutrient deficiencies may arise in the pineapple lands. A lowering of pH values thus occurs as Ca^{2+}, Mg^{2+}, K^+ and Na^+ ions are leached from the profile faster than they are released by mineral weathering (White, 1979). The soils in the pineapple lands may therefore be deficient in these cations which will represent a reduced fertility level as compared with the undisturbed soil under the natural vegetation.

The extract from Appendix E demonstrates that pH was inversely correlated with percentage clay (Figure 5.5) and directly related to organic carbon (Figure 5.6).

	SM	BD	P	IR	AS	SS	%SA	%SI	%C	OC
PH	0.206	-0.521	0.382	0.423	0.606	0.192	0.403	0.272	-0.662	0.628

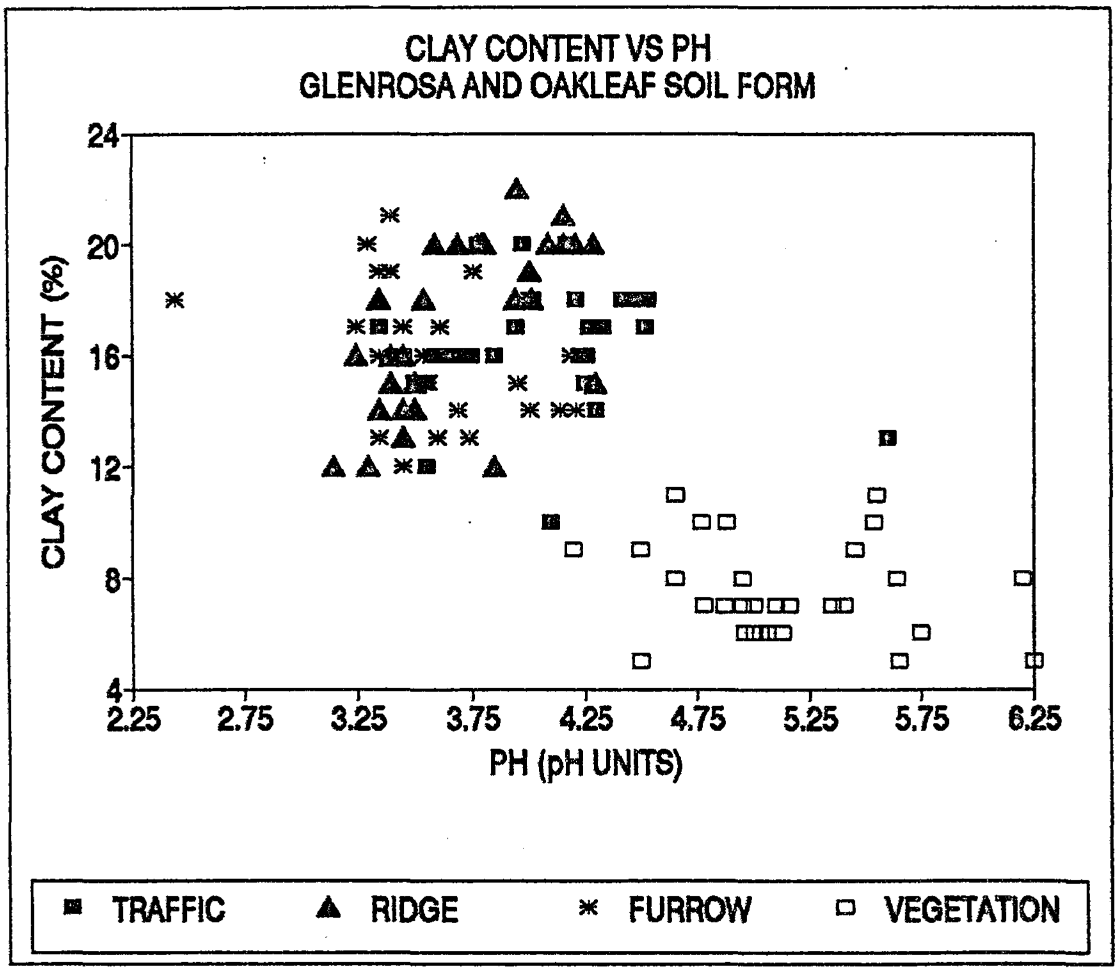


FIGURE 5.5: Scatterplot showing the relationship between clay content and pH for the four study sites

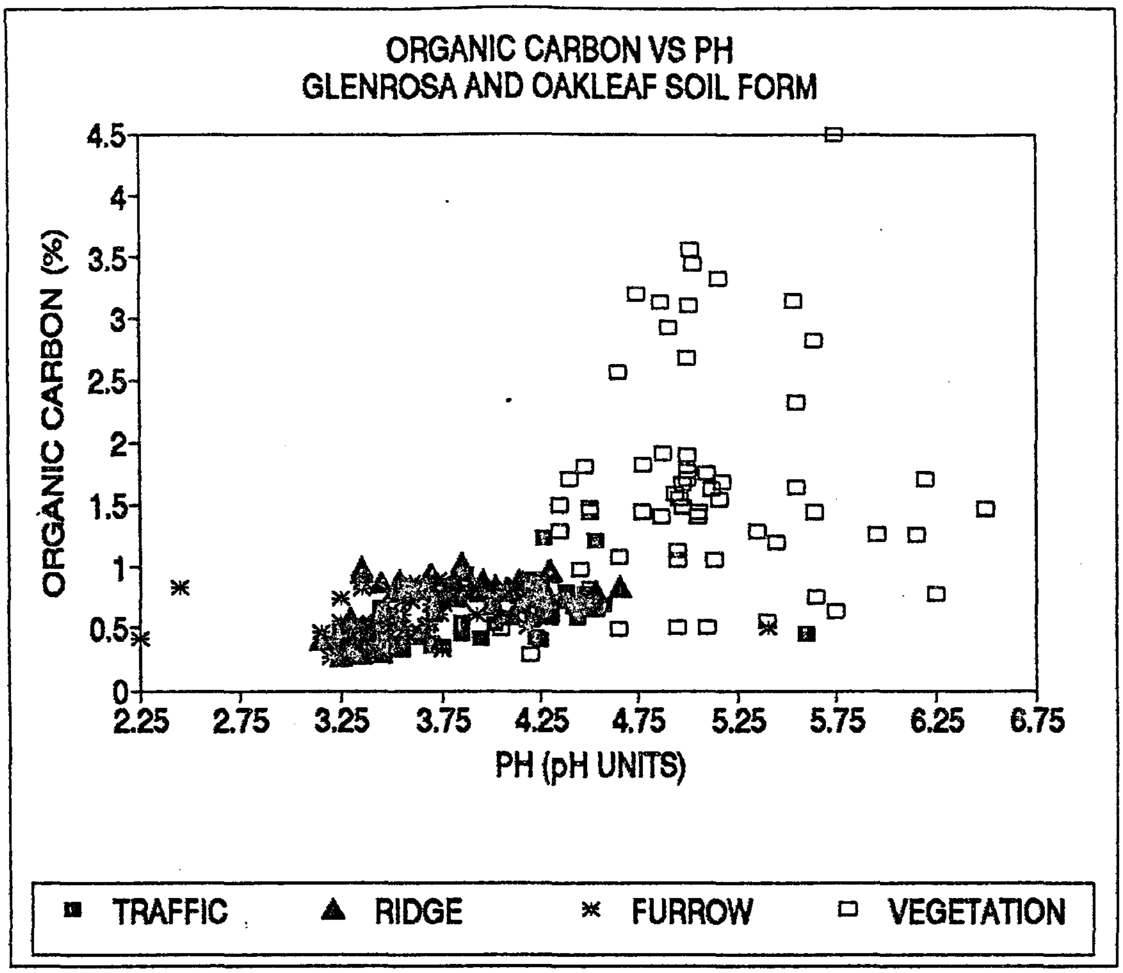


FIGURE 5.6: Scatterplot showing the relationship between organic carbon and pH for the four study sites

The scatter diagrams emphasize the higher pH values in the natural vegetation relative to the pineapple lands. The relationship between pH and other factors influencing erodibility is, however, not clearly understood and is an area that is recommended for further research.

5.1.10 SOIL STRUCTURE

Soil structure was classified using a soil profile description according to grade, size and shape (Hartmann, Hall and Dekker, 1989) (Table 5.11). Table 5.11 illustrates no structural differences between the Glenrosa pineapple lands and natural vegetation. However, there is greater structural development of the B horizon than the A horizon. The Oakleaf soil form, on the other hand, demonstrated greater structural development in the Oakleaf natural vegetation, compared to the pineapple lands. A moderate blocky subangular structure occurred in the A horizon of the natural vegetation while a weak granular structure occurred in the A horizon of the Oakleaf pineapple lands.

TABLE 5.11: Results of the soil structure classification

SOIL FORM AND STUDY SITE	SOIL STRUCTURE	
Glenrosa pineapple lands	A horizon:	Grade - single grained Size - fine Type - apedal
	B horizon:	Grade - moderate Size - fine Type - blocky subangular
Glenrosa natural vegetation	A horizon:	Grade - single grained Size - fine Type - apedal
	B horizon:	Grade - moderate Size - fine Type - blocky subangular
Oakleaf pineapple lands	A horizon:	Grade - weak Size - fine Type - granular
	B horizon:	Grade - moderate Size - medium Type - blocky subangular
Oakleaf natural vegetation	A horizon:	Grade - moderate Size - fine Type - blocky subangular
	B horizon:	Grade - moderate Size - medium Type - blocky subangular

5.1.11 PENETRABILITY

Penetrability was determined using the dynamic cone penetrometer method and histograms illustrating the results of the penetrability tests are presented in Appendix F. The soil in the traffic area of the pineapple lands was relatively difficult to penetrate in both the Glenrosa and the Oakleaf soil forms. However, the soil surface strength appears to be higher in the Glenrosa soil form than in the Oakleaf soil form. More blows were thus needed in the Glenrosa soils to penetrate to the same depth as in the Oakleaf soils. Only in three cases did the 60-blow allowance reach the maximum depth of one metre (Glenrosa 10 and Oakleaf 6 and 10). The soil surface strength is therefore high in the traffic areas. The increase in strength of the soil is a consequence of compaction of the soil by vehicular traffic. Generally, the trend is that once the top, highly compacted layer has been penetrated, there is a slightly more penetrable layer underneath. This trend is evident in Glenrosa 1, 4, 7, 8 and 9 and Oakleaf 9. However, in some cases, (Glenrosa 2 and 3 and Oakleaf 7 and 10), penetrability is initially high and decreases with depth since bulk density increases with depth. These areas can be explained by the fact that the test sites fell between the actual tracks on the road. These areas were not heavily compacted by machinery.

All the penetrability data on the ridges showed similar trends. Penetrability was initially very high, but becomes progressively more difficult with depth due to the increase in bulk density with depth. Relatively few blows (range of 0 to 9 blows) were required to reach the first 20 cm in depth. The increased penetrability of this area is due to the tillage and ridging processes which loosen the soil and break down soil structure. The decrease in bulk density and increase in air-filled porosity will result in a higher penetrability.

In certain cases (Glenrosa 4 and 10 and Oakleaf 8), there appears to be an increased resistance to penetration at approximately 30 to 50 cm. Since the soil is tilled to a depth of approximately 30 cm, this could possibly indicate the development of a plough-pan at these sites. Plough-pans are a consequence of repeated tillage at a similar depth which results in the formation of a smeared and compacted layer. This sub-surface compacted layer inhibits air and water movement (Ross, 1989).

Penetrability in the pineapple furrows was initially high and decreased with depth. It was, however, expected that penetrability would be lower initially, as a result of compaction due to foot traffic in the furrow. The results of the furrow data resemble the ridge data more closely than the traffic data. A possible reason for this increase in penetrability is the increased soil moisture in the pineapple furrow. Consequently, penetrability in this area could remain relatively high despite compaction resulting in high bulk density and low porosity levels.

Penetrability results in the undisturbed soils under natural vegetation varied greatly. However, in certain cases (particularly in Glenrosa 4, 6, 7, 8 and 10 and Oakleaf 8 and 10), the topsoil was easily penetrated. This could be explained by the fact that the natural vegetation consisted mainly of grasses. Grass has a well developed root system which increases the porosity of the soil. The high organic matter content of this area could also have increased the penetrability of the soils under natural vegetation due to the fact that a high organic content is related to a low bulk density. After the topsoil had been penetrated, the penetrability of the soils in the natural vegetation were relatively low. This is possibly because the soils in this area are undisturbed and hence more stable than those in the pineapple lands.

5.1.12 CATION EXCHANGE CAPACITY

The method used for the determination of cation exchange capacity was the ammonium acetate method. Due to financial constraints, only ten samples were analyzed (Table 5.12).

TABLE 5.12: Results of the Cation Exchange Capacity analysis (me/100g)

SOIL FORM	SAMPLE AREA	CEC	Ca	Mg	Na	K
G	T	3.118	0.513	0.313	0.098	0.308
G	R	3.135	0.281	0.081	0.026	0.090
G	F	3.160	0.194	0.075	0.013	0.104
G	V	4.200 3.248	2.250 1.375	0.688 0.563	0.072 0.068	0.394 0.581
O	T	4.625	3.000	0.975	0.189	0.577
O	R	3.064	1.813	0.450	0.130	0.039
O	F	4.510	2.000	0.444	0.049	0.373
O	V	6.818 6.260	3.688 3.375	1.513 1.600	0.196 0.293	0.662 1.002

where G = Glenrosa soil form

O = Oakleaf soil form

T = Traffic area

R = Pineapple ridge

F = Pineapple furrow

V = Undisturbed soil under natural vegetation

Due to the small sample size (N = 10), no statistical analyses were performed on the cation exchange capacity (CEC) data. However, it is clear that cation exchange capacities are greater in the natural vegetation than the pineapple lands. This tendency is repeated in both the Glenrosa and Oakleaf soil forms, but it is particularly noticeable in the Oakleaf soil form. A probable reason for the increased CEC in the natural vegetation is the higher percentage organic carbon that occurs at this site. This explanation is supported by Etherington (1975) who states that the CEC of sandy soils (soils of the natural vegetation) is associated with their organic content, but that of finer textured soils (soils of the pineapple lands) is a function of clay content. Further support is given to this theory of increased organic matter increasing CEC in the natural vegetation, by the fact that percentage clay was almost 50% lower in the natural vegetation than in the pineapple lands. The furrow site has a slightly higher CEC than the ridge site in both soil forms. This may be due to the fact that the topsoil is placed on the ridge in the ridging process. Exposure of the B horizon (zone of accumulation of clays) may thus occur in this manner. The increased clay content at the surface of the soil may increase the CEC of the furrow relative to that of the ridge. Exposure of clays becomes a realistic scenario when one considers the fact that the percentage organic carbon is higher in the ridge than in the furrow area. The slightly increased CEC in the traffic area may be due to compaction in this area which reduces infiltration and increases surface runoff. This increased runoff capacity may increase the amount of surface wash that occurs and result in preferential removal of sand. Again, exposure of clays may be the explanation for the increased CEC in the traffic area. The lower CEC in the pineapple lands is in accordance with the findings of Kulkarni and Savant (1977) who reported reduced cation retention and CEC as a result of the loss of organic compounds that accompany cultivation.

When considering individual cations, one can see that cultivation represents a major reduction in the amount of cations in the soil. From Table 5.13, it can be seen that pineapple cultivation results in a reduction of calcium, magnesium, sodium and potassium. Similar trends were discovered by Williams and Lipsett (1961) who noted a 14 per cent decrease in calcium, magnesium, potassium and sodium in cultivated lands as compared to pasture. The decrease in cations appears to be more marked in the Glenrosa than the Oakleaf soil forms. This is possibly due to the fact that the Glenrosa soil has been under cultivation for a longer period than the Oakleaf soil (cultivation was initiated in the Glenrosa soil in 1986 and in the Oakleaf soil in 1988).

TABLE 5.13: The percentage decrease in individual cations in the soils of the pineapple lands relative to those of the natural vegetation

SOIL FORM	SAMPLE AREA	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
Glenrosa	Traffic	71.7	50.0	-40.0	36.8
Glenrosa	Ridge	84.5	87.1	62.9	81.5
Glenrosa	Furrow	89.3	88.0	81.4	78.7
Oakleaf	Traffic	15.1	37.4	22.7	30.6
Oakleaf	Ridge	48.7	71.1	46.8	95.3
Oakleaf	Furrow	43.3	71.5	80.0	55.2

5.2 THE IMPLICATIONS OF THE VARIATIONS IN TERMS OF ERODIBILITY

As stated in Chapter 1, the key question to this thesis is:

"What effect does pineapple cultivation have on the factors affecting soil erodibility of representative soils in the pineapple growing regions of Bathurst, eastern Cape?"

In order to answer this question, the impact of the soil variations addressed in section 5.1 on soil erodibility must be discussed. Section 5.2 attempts to answer the key question by explaining the effects of pineapple cultivation on the factors controlling erodibility.

Soil moisture is considered to be a fundamental soil characteristic which affects many other soil attributes. Since Chepil (1956) found an inverse relationship between soil erodibility and the square of soil moisture, the highest erodibility would therefore be expected in the ridges. However, the relationship does not appear to hold at the other end of the scale in the pineapple lands, since one would not expect the pineapple furrows to have the lowest soil erodibility. Other factors influence soil erodibility and will increase the susceptibility of the soil to erosion in the furrow. However, conflicting evidence occurs in the literature since

Pall et al. (1982) suggests a direct relationship between soil water contents and erodibility. This implies that a higher soil erodibility would exist in the pineapple furrows. The increased moisture content in the furrows may be due to the greater clay content in the furrows which increases the water-holding capacity of these soils.

Bulk density and porosity are interdependent variables and show similar trends. Lower bulk density and higher porosity values occur in the soils in the natural vegetation and pineapple ridge, while foot and vehicular traffic result in compaction in the furrow and traffic areas, reducing the porosity and increasing the bulk density of these soils. A decrease in air-filled porosity and an accompanying increase in bulk density can have profound effects on infiltration rates. The slower rates of infiltration in the traffic and furrow areas may lead to an increased in surface runoff and thus a greater soil erosion hazard compared to that found in undisturbed soil.

Further evidence for lower erodibilities in the undisturbed soils under natural vegetation exist when considering differences in aggregate stability. The undisturbed soils under natural vegetation exhibited a mean aggregate stability of 95%, while the aggregate stability of the soils in the pineapple lands ranged from 82 to 86%. The implications of the loss of aggregate stability in the pineapple lands are multiple. Reduced stability of aggregates results in lower molecular cohesions and consequently the aggregates may be liable to shearing even at low moisture contents. The soil also becomes more prone to crusting under the impact of rainfall, and thus the reduced stability makes the soil susceptible to erosion by wind and water. Structural stability is therefore a vital control on erodibility.

The lowest shear strengths were found on the pineapple ridges. This is a consequence of the loosening of the soil for ridging and planting which results in disaggregation of peds and therefore a lower resistance to failure. Compaction of the furrow and traffic soils, on the other hand, results in an increase in resistance to shear failure. While lower surface shear strength of a soil appears to suggest that the soil is more erodible, this may not always be the case. The compacted soils of the traffic and furrow areas will have a high shear strength and a high erodibility due to the reduced infiltration capacity and greater likelihood of surface runoff and erosion. The soils of the pineapple ridge, however, have a low shear strength due to the disaggregation of peds and break down of soil structure during ridging, resulting in a higher erodibility, It is the intermediate shear strengths of the undisturbed soils of the natural vegetation which suggest a lower erodibility. This is due to their lower bulk density and high porosity which encourages infiltration of water as well as a stable aggregate structure.

The higher percentage sand content in the natural vegetation make these soils more resistant to transport, since a greater force is required to entrain them (Morgan, 1986). This implies that the soils in the natural vegetation will be less erodible than those in the pineapple lands. The silt particles are the most erodible since they are small enough to be relatively easily entrained, but not small enough to cohere together (Morgan, 1986). However, there were only minimal differences in silt content between the four sample sites. One would have expected the percentage clay content of the natural vegetation to be higher, so that the increased clay and organic matter contents (relative to the pineapple lands) would have improved the cohesiveness and aggregation of the soil and hence reduced soil erodibility. This was, however, not the case. The clay content was highest in the pineapple lands. A feasible explanation for the higher clay content in the furrows is the exposure of the B horizon in places. Another possible reason is preferential removal of sand particles in the pineapple lands due to surface wash. The restricted clay fraction (mean - 7.37%) in the undisturbed soils under natural vegetation suggest that these soils are the most susceptible to erosion (Evans, 1980), since clay functions as a binder to cement aggregates. However, organic matter is considered to be even more important in terms of stabilizing aggregates (Morgan, 1986), and may nullify the effects of a reduced clay fraction. Also, the inverse correlation between percentage clay and aggregate stability suggests that swelling clays exist which would increase the erodibility of the soils of the pineapple lands versus the natural vegetation.

Organic carbon was significantly higher in the soils of the natural vegetation than in the pineapple lands. The implications of a higher percentage organic carbon in the natural vegetation are increased cohesiveness, increased water retention capacity and a stable aggregate structure (Morgan, 1986). All of these factors point to a lower soil erodibility in the undisturbed soils under natural vegetation than those under pineapple production.

The soils in the pineapple lands are more acidic than those in the natural vegetation, reducing the availability of cations in these soils. Calcium, magnesium, potassium and sodium may be leached out of the soil profile faster than they can be replaced by mineral weathering, resulting in a reduced fertility in the pineapple lands. The cation exchange capacity results confirm this finding. While it is, however, very difficult to prove that a loss of fertility in the pineapple lands would increase the susceptibility of the soil to erosion, this represents a distinct possibility. The relationship between pH and soil erodibility is, however, a poorly understood and deceptively complex topic which requires further research.

The results of the penetrability tests indicated a lower penetrability in the soils of the traffic and furrow areas compared to those of the ridge and natural vegetation areas. The compaction in the traffic and furrow areas reduces porosity and increases bulk density. These processes will reduce penetrability and infiltration rates, making the traffic area ideal for surface overland flow. The smooth surfaces of the road and furrow also facilitate runoff. Although the soil surface strength is high, no vegetation occurs in these areas to bind the soil particles together. This suggests a higher erodibility in the traffic and furrow areas. Although the soils of the natural vegetation have a lower soil surface strength and a higher penetrability, the higher organic carbon levels and extensive root systems that occur reduce the bulk density and therefore increase infiltration rates in this area. Rainfall will therefore infiltrate into the soil rather than contribute to overland flow which is highly erosive. The penetrability results therefore also suggest that a lower erodibility occurs in the natural vegetation.

The higher cation exchange capacities that occur in the undisturbed soils under natural vegetation suggest a lower erodibility in these areas. This finding is in accordance with research reported by Pitty (1978) who stated that an inverse correlation occurs between CEC and erodibility. The greater amounts of calcium and magnesium that occur in the soils under the natural vegetation also point to a reduced erodibility in this area. Similar results have been found by Wallis and Stevan (1961), Evans (1980) and Singer et al. (1980). In the case of sodium, the natural vegetation area exhibited higher levels of sodium than the pineapple lands. This result is contrary to expectations since sodium is known to increase the dispersiveness of soils (Morgan, 1986). In the traffic area of the Glenrosa soil form, a higher sodium level would be expected to increase erodibility due to chemical dispersion. Wallis and Stevan (1961), however, reported no significant relationship between erodibility and percentage sodium or potassium.

To conclude, the lower CEC of the soils in the pineapple lands relative to those of the natural vegetation suggest a weaker buffer mechanism to minimise changes in the pineapple lands (Pitty, 1978). The undisturbed soils under natural vegetation would thus perhaps represent a more stable chemical environment.

In an attempt to determine the order of magnitude of difference in erodibility between the four sample sites, Bouyoucos' (1935) clay ratio was applied to the data collected from the four sample sites. The clay ratio is a measure of the amount of binding material in the soil, expressed as a direct index of erodibility:

$$\frac{\%\ \text{Sand} + \%\ \text{Silt}}{\%\ \text{Clay}} \qquad \text{(E5.1)}$$

The clay ratio was selected since it was the only ratio discussed in the development of soil erodibility theory (Chapter 3), for which data was readily available.

The clay ratio does, however, have a number of limitations. This ratio, proposed by Bouyoucos in 1935, was a logical development of the theory that soil particles must be dispersed before erosion can occur. While it has the merit of simplicity and can be derived from basic analytical data, it is now known that undispersed soil may also be removed by erosion (Bryan, 1968). Other criticisms of the ratio as in index of erodibility include two points:

1. When the clay content drops lower than 10%, the ratio is liable to be inaccurate as a consequence of high water transmission status. Virtually no runoff will occur and erosion will be purely a function of splashing by raindrops. The useful range of the ratio is thus restricted, and it should be treated with caution when the clay ratio falls below 10%.

2. Another even more important criticism is that the clay ratio places undue weight upon the importance of clay as a binder and ignores the influence of organic matter which may be a more important aggregate cementing agent.

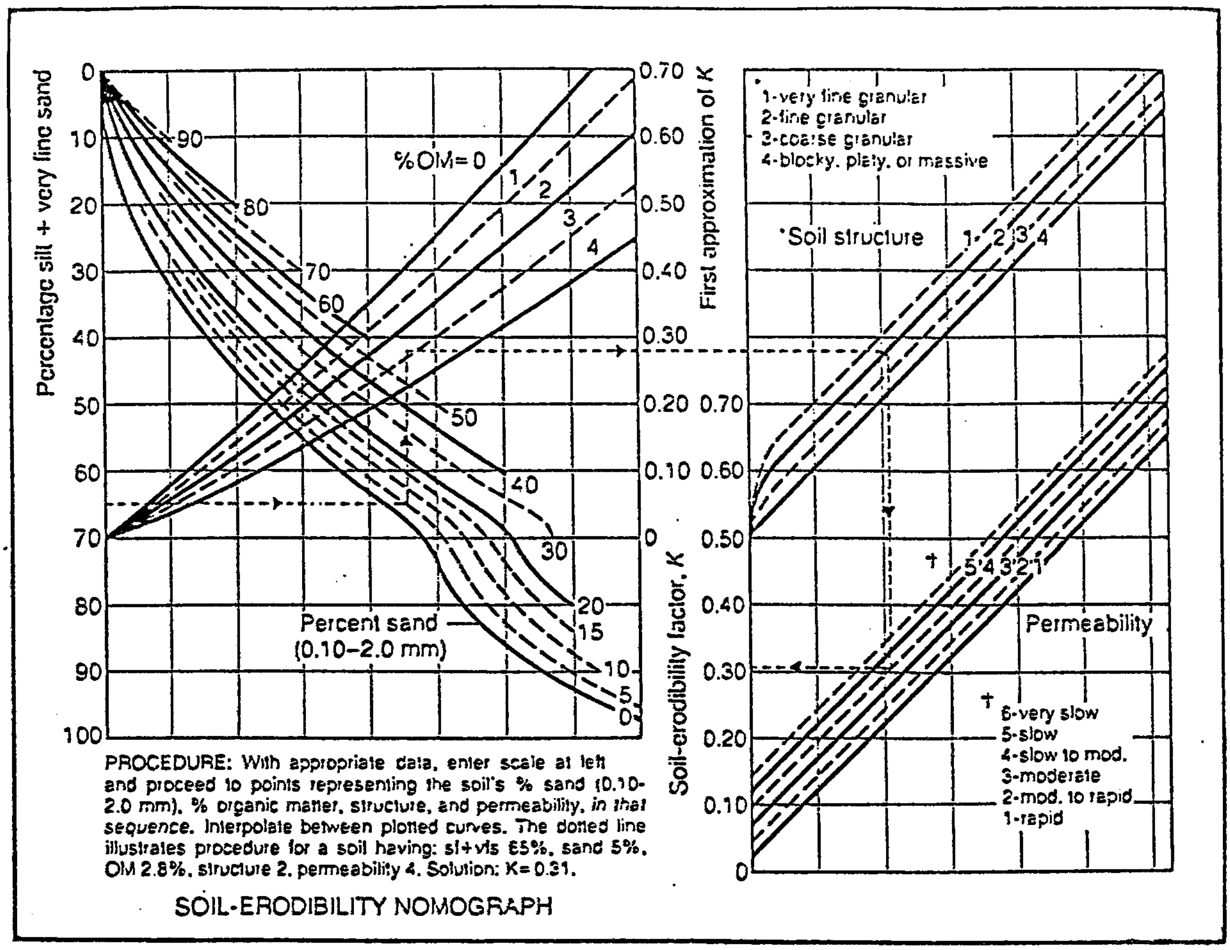
The clay ratio was determined using the mean values of the various particle sizes (Table 5.14). The ratio is smallest in soils which are considered to be 'non-erodible' and greatest in soils which are considered to be very erodible.

TABLE 5.14: The clay ratio as an index of erodibility

SOIL FORM	TRAFFIC AREA	PINE. RIDGE	PINE. FURROW	NATURAL VEGET.
GLENROSA+OAKLEAF	5.129	4.837	5.179	12.564
GLENROSA	5.757	5.881	4.913	13.150
OAKLEAF	4.625	4.068	5.470	12.043

The results of the clay ratio analysis thus suggest that the pineapple lands have a lower erodibility than the natural vegetation. This trend is contrary to expectations and is a consequence of the limitations of the clay ratio. Since the mean percentage clay in the soils of the natural vegetation is only 7.37%, high infiltration rates will occur, reducing surface runoff and thus soil erodibility in this area. The clay ratio also ignores the aggregate stabilizing effect of the increased organic carbon content in the soils under the natural vegetation. While a high clay ratio illustrates increased cohesiveness and thus strength of a soil, the ratio is inadequate since it ignores many of the vital factors controlling erodibility; namely infiltration rate, aggregate stability and organic carbon. The ratio does, however, indicate a higher erodibility in the Glenrosa soil form compared to the Oakleaf soil form.

Although insufficient data exists to apply the nomograph for computing the K value of soil erodibility for use in the Universal Soil Loss Equation (Figure 5.7), an evaluation of the nomograph parameters in terms of the erodibility of the four study sites may confirm some of the findings discussed above.



SOIL-ERODIBILITY NOMOGRAPH

FIGURE 5.7: Nomograph for computing the K value of soil erodibility (Wischmeier, Johnson and Cross, 1971).

While percentage silt remains fairly constant between the four study sites, the percentage sand is generally higher in the soils of the natural vegetation. The organic matter content is also much greater in the soils of the natural vegetation relative to those of the pineapple lands. Already, based on a first approximation of K (Figure 5.7), the soils of the natural vegetation would therefore demonstrate a lower erodibility value than the soils of the pineapple lands. The moderate blocky subangular structure of the Oakleaf natural vegetation soils relative to the weak granular soils in the pineapple lands also suggests a lower erodibility in the undisturbed soils of the natural vegetation. Using infiltration rate data as a surrogate for permeability, the nomograph illustrates that the rapid infiltration rates of the soils under vegetation result in a lower K value relative to the pineapple lands on which infiltration is restricted as a consequence of compaction in the traffic and furrow areas. The K value therefore suggests that the soils of the natural vegetation have a lower erodibility than those of the pineapple lands. Therefore, although the K value has a number of shortcomings (outlined in Chapter 3), it does consider most of the primary factors controlling erodibility, such as soil texture, organic carbon and permeability (infiltration rate) in the pineapple lands.

In conclusion, two basic processes occur which suggest that pineapple cultivation practices lead to increased soil erodibility:

1. Initially the ridging of the soil breaks up and loosens the soil, leading to aggregate destruction;
2. Compaction of the furrow and traffic area leads to increased bulk density and reduced porosity and infiltration rates which will increase runoff and erosion hazard.

The undisturbed soils under natural vegetation, on the other hand, demonstrate higher organic carbon percentages which improve the aggregate stability of the soil. Infiltration rates are also higher, thus increasing the water absorption capacity of the soil and reducing the amount and rate of surface runoff. This will reduce the likelihood of excessive soil loss in the natural vegetation.

CHAPTER 6

DISCUSSION OF THE VARIATION IN FACTORS CONTROLLING SOIL ERODIBILITY WITHIN SAMPLE SITES

Chapter 5 discussed the variation in factors controlling soil erodibility between the traffic area adjacent to pineapple lands, pineapple ridges, pineapple furrows and undisturbed soil under natural vegetation and their implications in terms of erodibility. The current chapter analyses variations of selected soil characteristics within the traffic, ridge, furrow and natural vegetation soils. The implication of these spatial variations up and down the slope of each sample site will also be addressed.

6.1 VARIATIONS WITHIN SAMPLE SITES

The techniques used to quantify the factors influencing soil erodibility are as discussed in Chapter 4. The SURFER version 4 computer package (SURFER, 1990) was used to generate the isoline plots illustrating the variations in soil characteristics in space. The inverse distance routine was adopted for gridding the data in order to produce the isoline plots The results of the isoline analysis are presented in Figures 6.1 to 6.9.

SOIL MOISTURE (% weight)	BULK DENSITY (g.cm^{-3})	POROSITY (% volume)	INFILTRATION RATE (ml. minute^{-1})	AGGREGATE STABILITY (% volume)	SHEAR STRENGTH (kPa)
24+	2·0+	50+	800+	92+	105+
18–23	1·6–1·9	40–49	500–799	84–91	80–104
12–17	1·2–1·5	30–39	200–499	76–83	55–79
6–11	0·8–1·1	20–29	100–199	68–75	30–54
0–5	0·4–0·7	10–19	0–99	60–67	5–29

SAND CONTENT (%)	CLAY CONTENT (%)	SILT CONTENT (%)	ORGANIC CARBON (%)	pH
92+	20+	12+	2·0+	6+
84–91	15–19	9–11	1·5–1·9	5–5·9
76–83	10–14	6–8	1·0–1·4	4–4·9
68–75	5–9	3–5	0·5–0·9	3–3·9
60–67	0–4	0–2	0–0·4	2–2·9

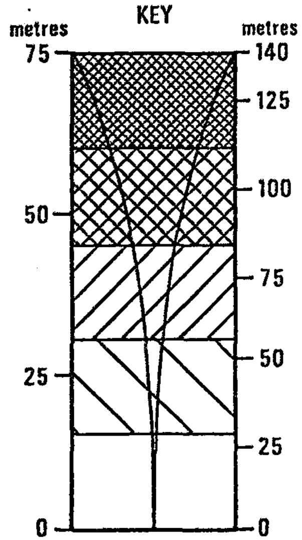


FIGURE 6.1: Key to isoline plots

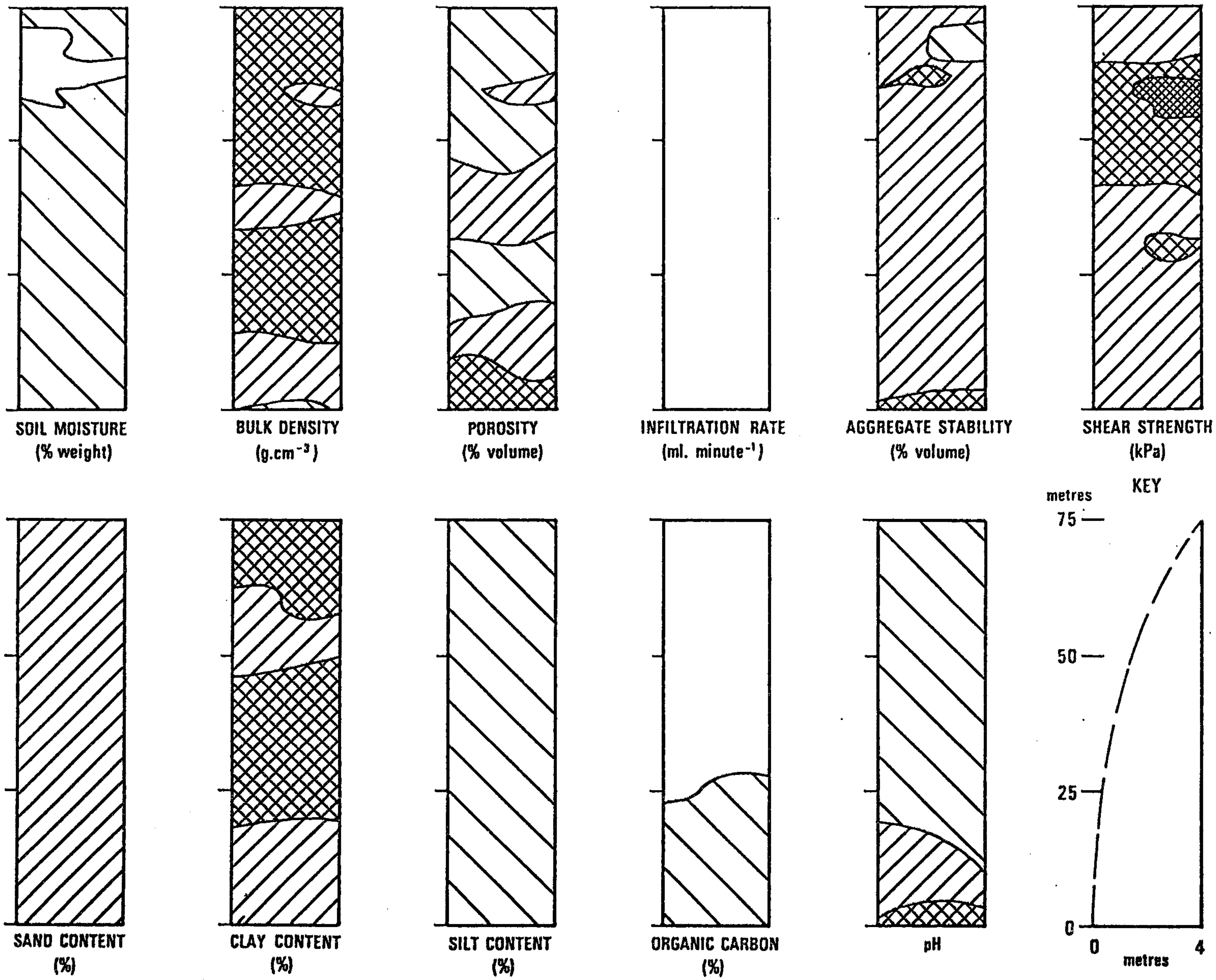


FIGURE 6.2: Isoline plots showing the spatial variation in factors influencing soil erodibility in the traffic area, Glenrosa soil form.

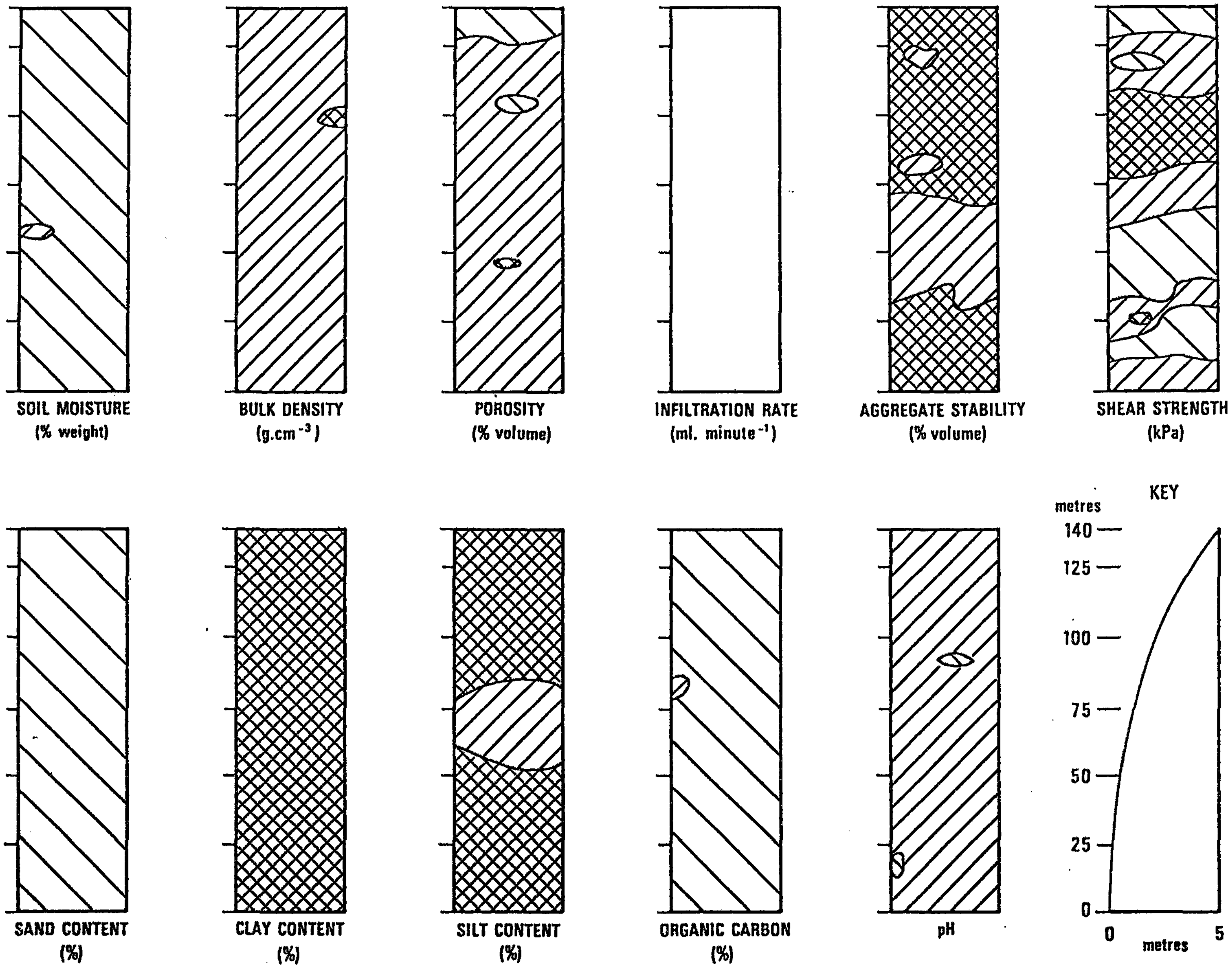


FIGURE 6.3: Isoline plots showing the spatial variation in factors influencing soil erodibility in the traffic area, Oakleaf soil form.

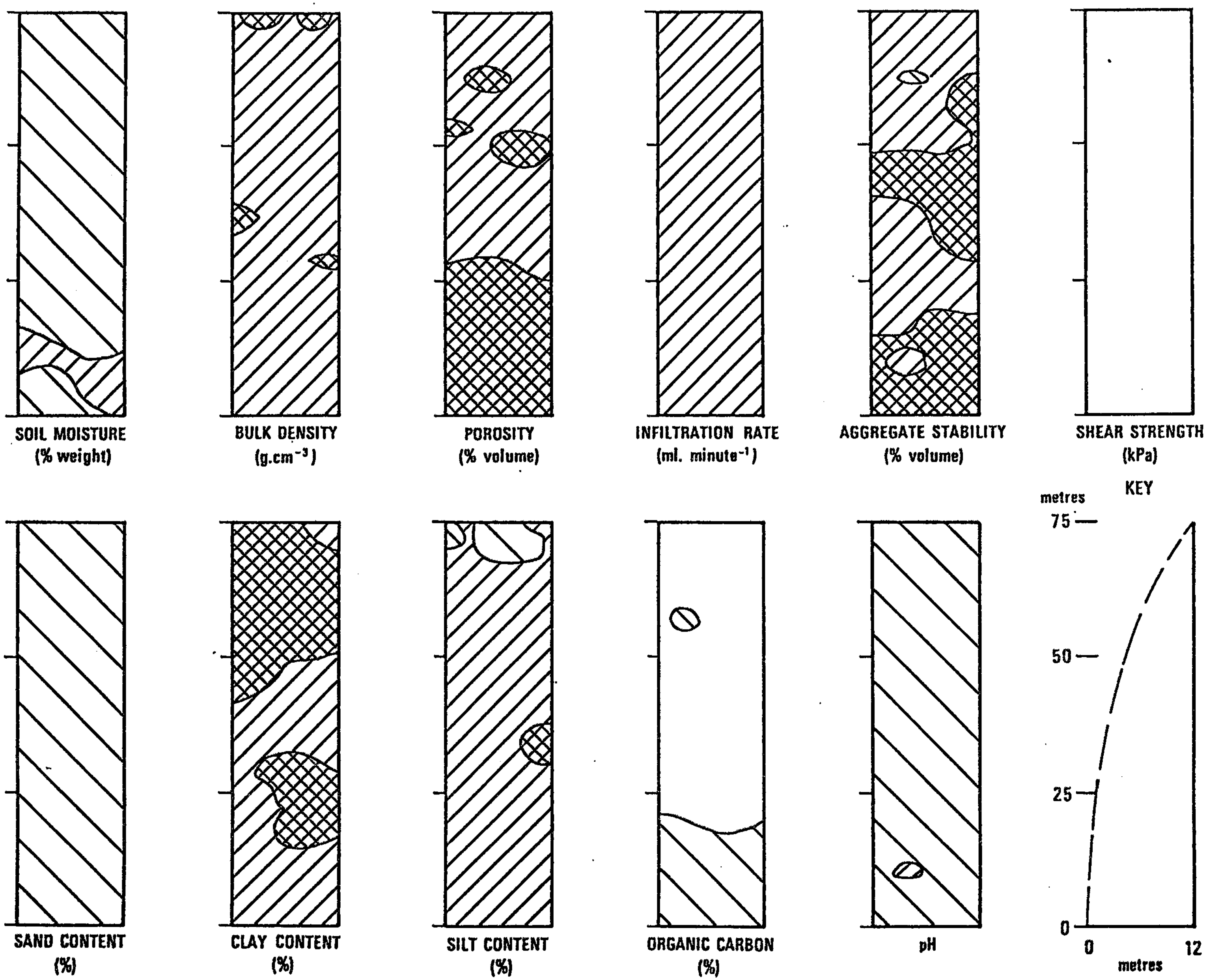


FIGURE 6.4: Isoline plots showing the spatial variation in factors influencing soil erodibility in the pineapple ridge, Glenrosa soil form.

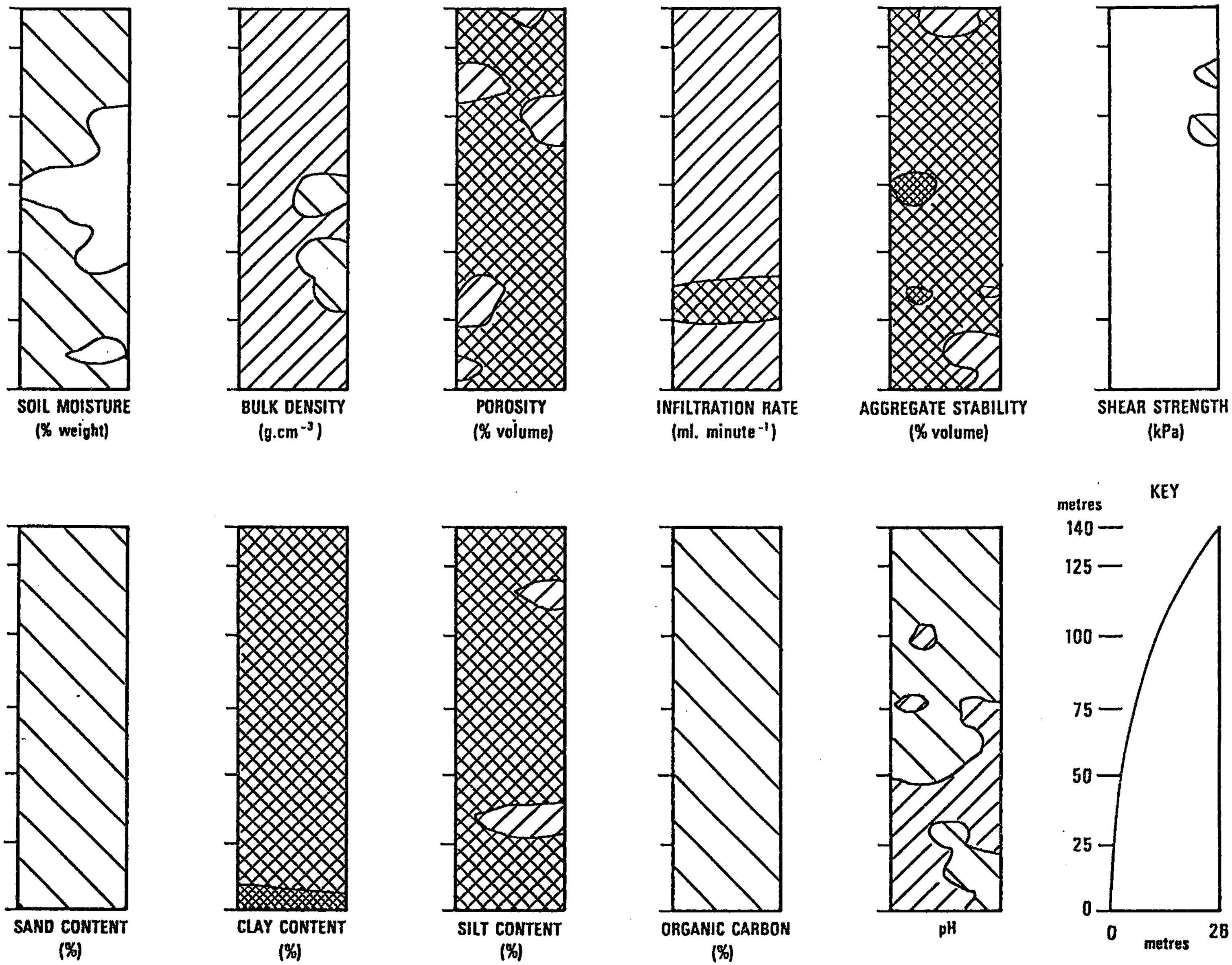


FIGURE 6.5: Isoline plots showing the spatial variation in factors influencing soil erodibility in the pineapple ridge, Oakleaf soil form.

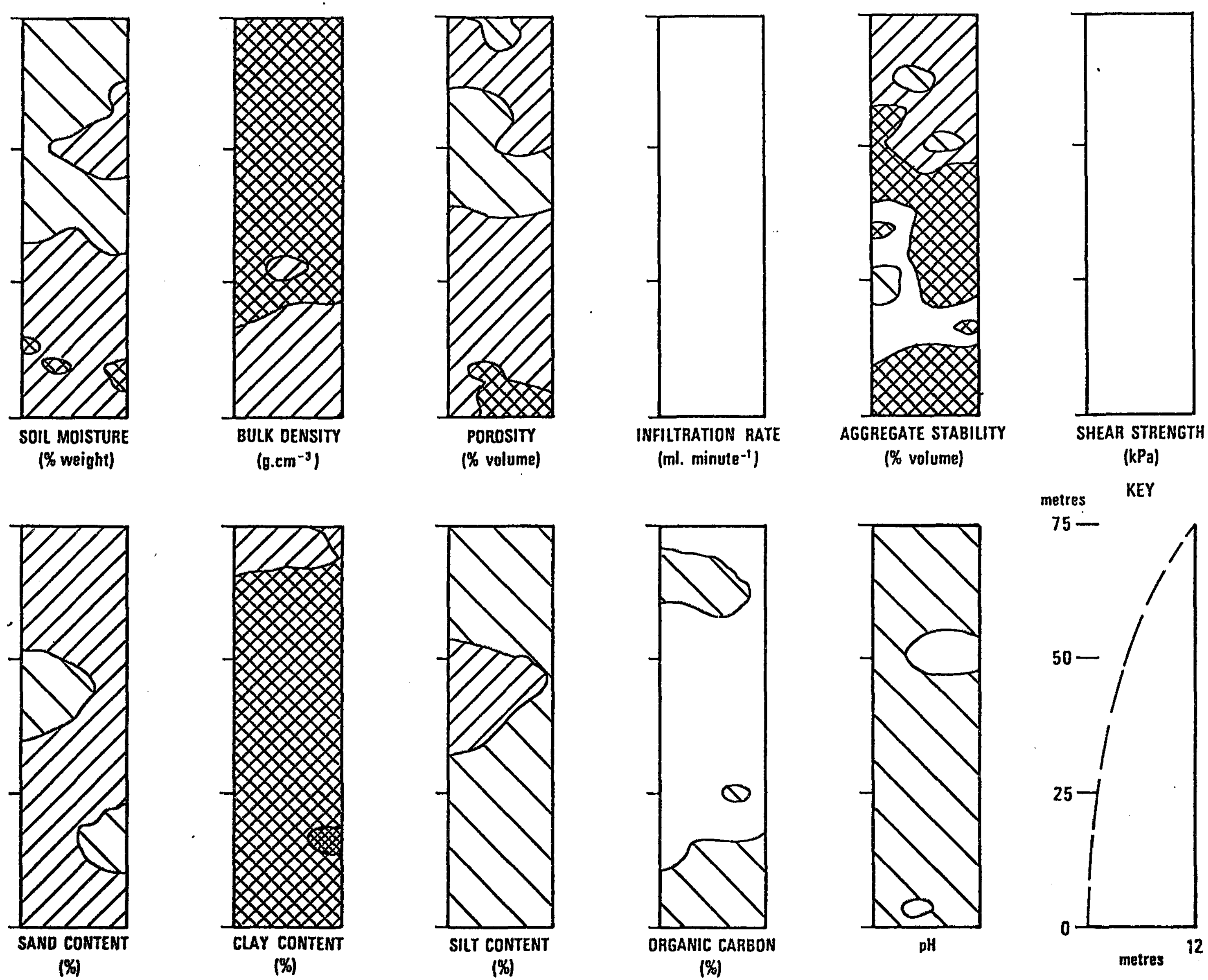


FIGURE 6.6: Isoline plots showing the spatial variation in factors influencing soil erodibility in the pineapple furrow, Glenrosa soil form.

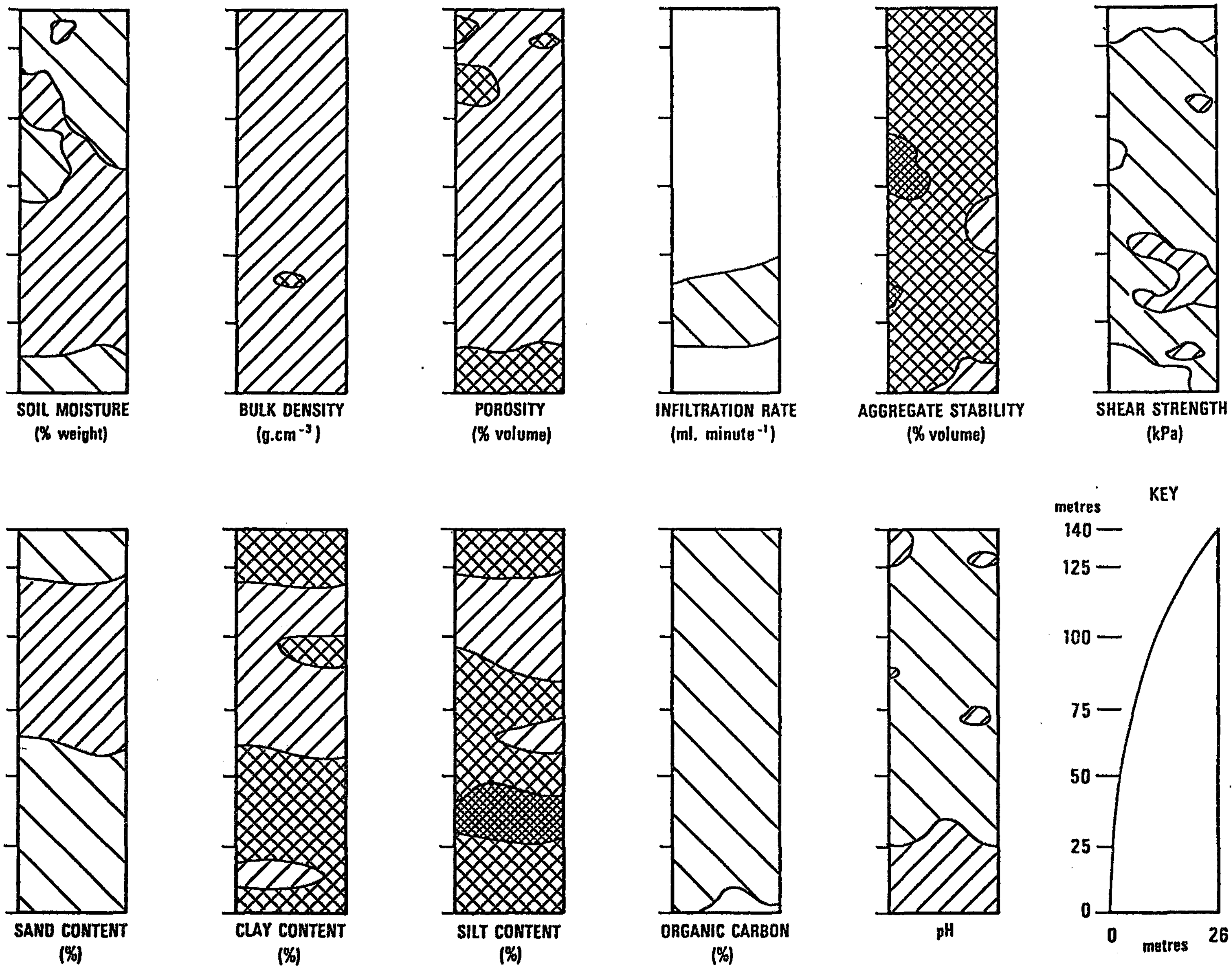


FIGURE 6.7: Isoline plots showing the spatial variation in factors influencing soil erodibility in the pineapple furrow, Oakleaf soil form.

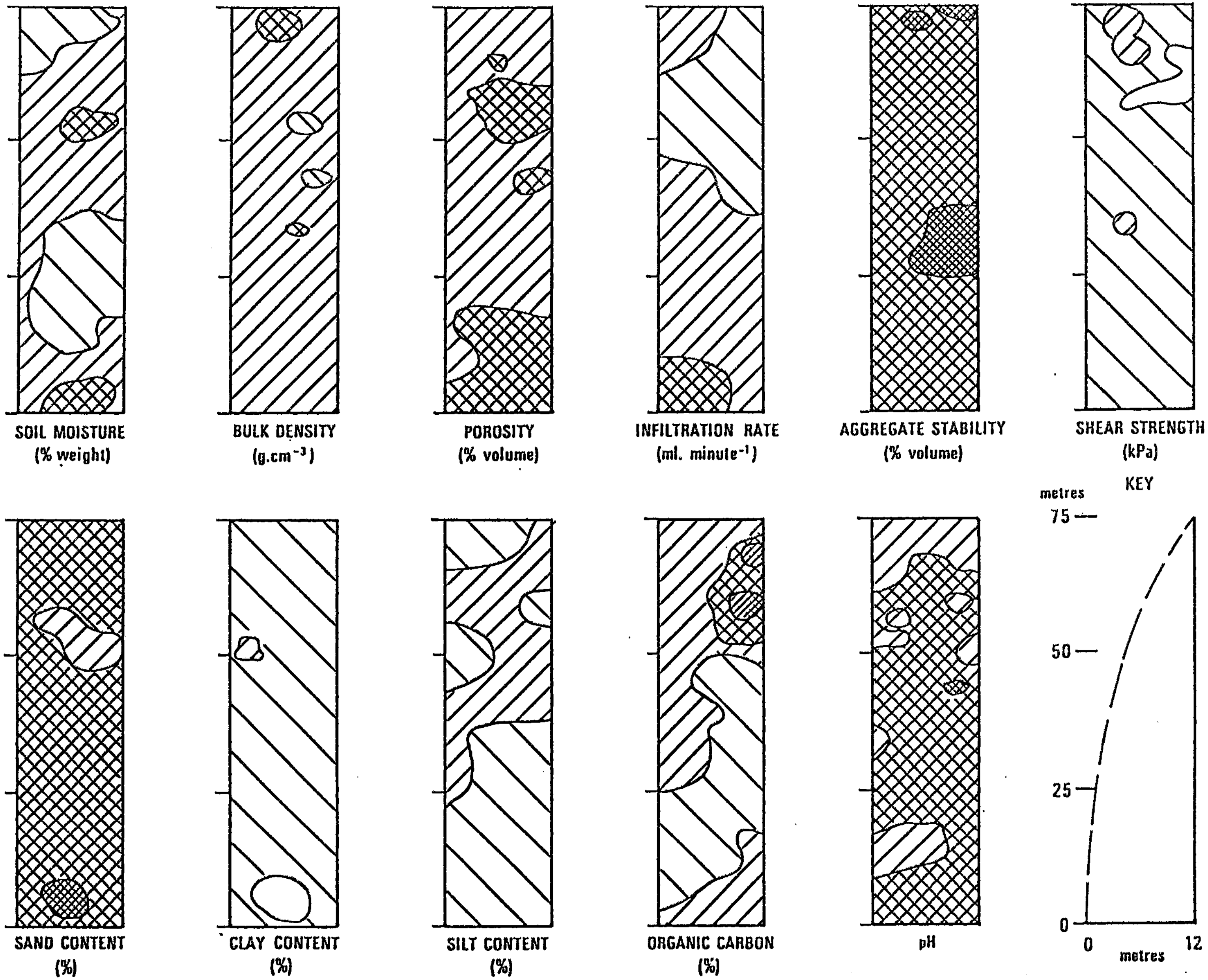


FIGURE 6.8: Isoline plots showing the spatial variation in factors influencing soil erodibility in the undisturbed soil under natural vegetation, Glenrosa soil form.

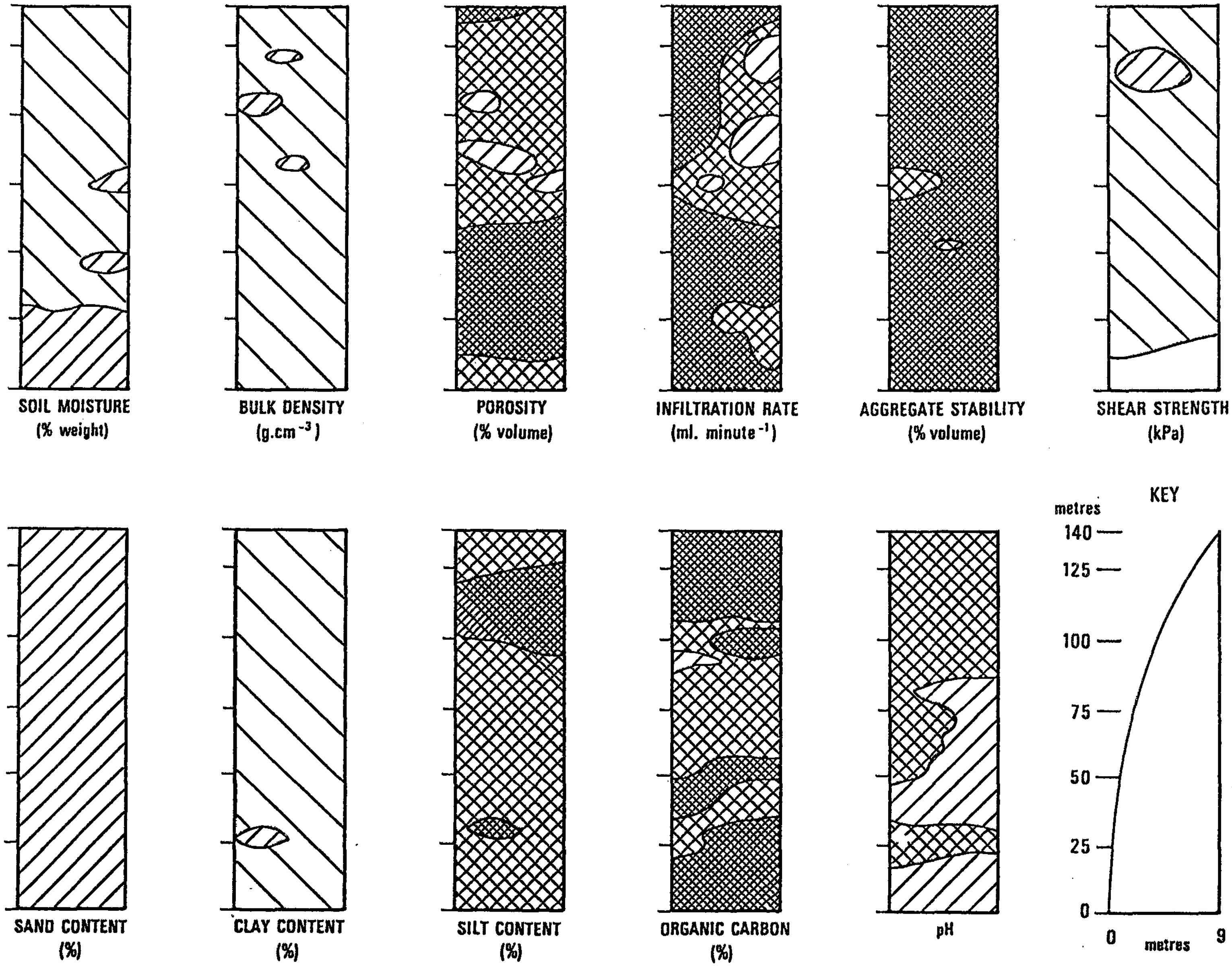


FIGURE 6.9: Isoline plots showing the spatial variation in factors influencing soil erodibility in the undisturbed soil under natural vegetation, Oakleaf soil form

6.1.1 TRAFFIC AREA ADJACENT TO PINEAPPLE LANDS

Soil moisture remained relatively constant down the slope. The Glenrosa soil form, however, demonstrated a slightly lower soil moisture in the upslope regions. This was probably due to downslope movement of water in the soil, which is likely to result in preferential development of surface storage and runoff in the downslope area. The upslope region will therefore be able to accept more rainfall before the initiation of overland flow. However, the intensity of the rainfall will affect this relationship since low intensity rainfall is likely to infiltrate, while high intensity rainfall will probably initiate surface runoff. Bulk density and porosity appeared to be relatively uniform in the Oakleaf soil form. The Glenrosa soil form, however, displayed increased bulk density and decreased porosity values in the upslope regions compared to the footslope. This is contrary to expectations since the higher soil moisture values in the downslope area were anticipated to increase the likelihood of aggregates to shear, and hence vehicular compaction and bulk densities at the footslopes relative to the top of the slope. Infiltration rates remained spatially uniform in both the Glenrosa and the Oakleaf soil forms, but this may have been a consequence of the relatively sparse data base for this soil variable. However, the lower bulk density and increased porosity values at the footslope of the Glenrosa soil form suggest that a higher infiltration rate will occur at the footslope region. Aggregate stability was generally uniform down the slope in the Glenrosa soil form increasing at the bottom of the slope. An area of decreased aggregate stability occurs at approximately 40 m up the slope in the Oakleaf soil form. The probable explanation for this reduction in stability is the existence of a waterway in this area. The stability of the aggregates above this waterway will be reduced on wetting since wetting may weaken the aggregates by lowering their cohesiveness and softening the cements between peds (Briggs and Courtney, 1985). A corresponding reduction in shear strength is observed at approximately 50 m up the slope in the Oakleaf soil form. The general spatial variations in shear strength in the traffic area were highly variable, particularly in the Oakleaf soil form. This is likely to be a response to the difference between values measured on and between the vehicle tracks. However, shear strength values were generally higher in the upslope areas.

When considering the texture of the soils, it can be seen that texture remained relatively constant down the traffic slope. The clay content was higher in the upslope areas of the Glenrosa soil form possibly as a consequence of preferential removal of the sand particles by surface wash. Organic carbon remained constant in the Oakleaf soil form, but was higher in the downslope regions of the Glenrosa soil form. Soil pH increases downslope in the Glenrosa soil form, reflecting an increase in the availability of cations in the downslope direction, but remained uniform in the Oakleaf soil form.

6.1.2 PINEAPPLE RIDGES

Soil moisture was again slightly higher towards the downslope areas, particularly in the Glenrosa soil form. Bulk density was also relatively constant over space, but porosity increased in the downslope areas of the Glenrosa pineapple ridge. Infiltration rates were again uniform down the slope, but aggregate stability values increased down the pineapple ridge slope in the Glenrosa soil form. Shear strength was consistently low in both soil forms.

Soil texture in the pineapple ridges repeated similar trends to those occurring in the traffic areas. Texture was therefore relatively constant except for the increased clay content in the upslope areas of the Glenrosa soil form. This increased clay content appears to correspond to a decrease in aggregate stability which is contrary to expectations since clay is considered to be an aggregate cementing agent. However, the correlation coefficients confirm this finding, since an inverse relationship occurs between clay content and aggregate stability. The percentage organic carbon was higher at the bottom of the Glenrosa slope, corresponding to an increase in aggregate stability in this area. Organic carbon can thus be considered to be a more vital aggregating agent than clay content in the pineapple lands, promoting a more stable aggregate structure in the pineapple ridges. PH was constant in the Glenrosa soil form, but increased in the downslope direction in the Oakleaf soil form.

6.1.3 PINEAPPLE FURROWS

The pineapple furrow isoline plots illustrate greater variability than the traffic or ridge plots. It can clearly be seen that soil moisture decreases down the pineapple furrow slope. The function of the furrow as a runoff conduit possibly facilitates this relationship since water is rapidly removed from the top of the slope. Bulk density was again fairly uniform, decreasing towards the bottom of the slope in the Oakleaf soil form. Since bulk density and porosity are interdependent variables, porosity demonstrated the opposite trend. Infiltration rate was uniformly low, but increased slightly towards the bottom of the Oakleaf furrow slope as a consequence of the increased porosity in this area. Aggregate stability was highly variable, demonstrating no particular trend. Similar results occurred for shear strength of the Oakleaf soil form, while the shear strength of the Glenrosa soil form was uniformly low.

Texture was remarkably variable in both the Glenrosa and Oakleaf soil form. The sand content was generally higher at the top of the furrow slope, while silt content was higher at the bottom of the Oakleaf slope. Clay content was generally uniform (the Glenrosa soil form) or varied in no particular pattern (Oakleaf soil form). The organic carbon content of the Glenrosa soil form is higher at the bottom of the slope, again corresponding to greater stability of aggregates in this area. The organic carbon content, however, also corresponded to a decrease in bulk density in the Glenrosa soil form. The organic carbon content of the Oakleaf soil was spatially homogenous. The pH of the Oakleaf soil decreased in a downslope direction, while the pH remained constant in the Glenrosa soil form.

6.1.4 UNDISTURBED SOIL UNDER NATURAL VEGETATION

The most outstanding feature of these spatial variations in factors influencing erodibility is, in fact, their variability. The only single soil characteristic that showed a completely uniform distribution over space was sand content in the Oakleaf soil form. This is a result of the heterogeneity of biological activity that occurs in this area as compared to the relative uniformity of activity that occurs in the pineapple lands. Another interesting attribute of this area is that many of the soil characteristics fall into the highest category possible. This trend is particularly noticeable in the Oakleaf soil form.

When considering the spatial variations downslope, Figures 6.8 and 6.9 illustrate higher soil moisture values in the downslope regions. Bulk density demonstrated no major increases or decreases over space. Porosity, however, was generally higher in the downslope regions. As a result of increased porosity, the downslope regions also demonstrated a higher infiltration rate. Aggregate stability was uniformly high in both the Glenrosa and the Oakleaf soil forms, and the shear strength values in the Glenrosa soil form also demonstrated remarkable uniformity. Shear strength in the Oakleaf soil form, however, was reduced in the downslope areas. The most remarkable feature of the spatial variations in soil texture in the natural vegetation was the increased silt content of the upslope regions, a trend portrayed in both the Oakleaf and Glenrosa soil forms. The spatial variation of percentage organic carbon demonstrated a higher value in the upslope region of the Glenrosa soil. The isoline plot for the Oakleaf soil form illustrated higher levels of organic carbon at the top and bottom of the slope, with reduced amounts of organic matter in the middle of the slope. Soil pH was higher in the upslope regions of the Oakleaf soil form and higher in the downslope regions of the Glenrosa soil form.

6.2 THE IMPLICATIONS OF THE VARIATIONS IN TERMS OF ERODIBILITY

The lower bulk density and higher porosity levels at the bottom of the Glenrosa slope suggest an increased infiltration rate in this area. The isoline plots, however, do not always portray this trend, possibly due to either the relatively small sample size for this variable or the difficulty of categorizing the wide range of infiltration rates obtained. Since it is the infiltration capacity which ultimately determines the magnitude of runoff and the probability of erosion (Ross, 1989), the downslope region is likely to have a lower susceptibility to erosion. This supposition is confirmed by the occurrence of higher organic carbon and corresponding aggregate stability values in the downslope soils of the Glenrosa traffic area, pineapple ridges and furrows and the natural vegetation areas. Organic carbon is therefore important in improving cohesiveness, water retention capacity and promoting a stable aggregate structure (Morgan, 1986). Clay content is also considered to be an important aggregating cementing agent (Bryan, 1968). The percentage clay, however, is higher in the upslope region of the soils in the Glenrosa traffic area and pineapple ridge, implying that the increased cohesiveness of aggregates will lower the erodibility at the top of the slope. However, from the correlation coefficients (Appendix E) as well as the isoline plots, one can see that clay content is inversely related to aggregate stability ($r = -0.556$) in the Glenrosa soil form. Clay content is, however, also negatively correlated with infiltration rate ($r = -0.449$) in the Glenrosa soil form. These correlations suggest that since clay content is higher and infiltration correspondingly lower in the upslope regions of the Glenrosa traffic and ridge areas, a higher erodibility exists at the top of the slope.

More evidence for a higher erodibility in the upslope areas exists as a consequence of the higher percentage silt at the top of the undisturbed soil under natural vegetation slope. Silt particles are highly erodible due to their lack of cohesiveness and relatively small particle size. The shear strength of the Glenrosa soils was not highly variable in space up and down the slope in the pineapple ridges and furrows and natural vegetation. The shear strength of the traffic area, however, was higher towards the top of the slope. Since a high shear strength would suggest a highly compacted soil, erodibility is likely to be higher at the top of the slope due to the increased potential for surface runoff and soil loss.

The variations in bulk density, porosity, aggregate stability and organic carbon suggest that all four areas in the Glenrosa soil form are likely to have a higher erodibility at the top of the slope compared to the bottom of the slope. However, other factors such as the increase in runoff down the slope will also affect this relationship. The implications of variations in soil factors in terms of erodibility are therefore often not direct nor easy to understand, making a definitive statement about increased or decreased erodibility in any spatial area extremely difficult.

In terms of erodibility, the Oakleaf soil form portrays a highly complex picture. The traffic area of the Oakleaf soil form showed very little variation of soil characteristics controlling erodibility over space. The only variables not illustrating a uniform distribution were aggregate stability, shear strength and silt content. Aggregate stability was lowest in the midslope regions suggesting a higher erodibility in this area. This assumption is confirmed by a high shear strength in the middle of the slope, indicating a compacted surface soil. However, the silt content is lowest in the midslope regions and this implies a lower erodibility in the midslope regions since silt particles are the most erodible. Conflicting results thus occur when interpreting soil characteristics in terms of erodibility in the traffic area of the Oakleaf soil form.

In the pineapple ridge area, the soil characteristics controlling erodibility vary only slightly. The only notable variation is the increased infiltration rate and decreased silt content at approximately 25 - 40 m from the bottom of the slope. Since an increased infiltration rate decreases surface runoff and silt particles are highly erodible, a lower erodibility appears to exist in this area of the Oakleaf ridge.

The isoline plot of the Oakleaf furrow (Figure 6.7) also illustrates a higher infiltration rate approximately 20 to 40 m from the bottom of the slope. However, there is also an increase in the highly erodible silt-sized particles in this area. There appears to be an increased sand content 60 to 120 m from the bottom of the slope, corresponding to a decreased clay and silt content in this area. Since the aggregate stability and organic carbon content of the Oakleaf furrow soil are essentially uniform, the conflicting evidence presented would make it extremely difficult to imply a greater or lesser soil erodibility in any single area of the furrow slope.

A similar situation exists in the undisturbed Oakleaf soil under natural vegetation . The increased porosity and infiltration rates of the soil between 15 and 60 m from the bottom of the slope suggest a lower soil erodibility in this area. However, the organic content is generally lower in this area, implying a higher soil erodibility. Also, a greater percentage silt occurs between approximately 100 and 125 m, suggesting that this area of the slope has a lower resistance to erosion. However, the organic carbon content of the soil is higher in this area, implying a lower erodibility. The isoline analysis of the Oakleaf soil form thus demonstrates the complexity and multiplicity of the spatial variations in factors influencing soil erodibility on a hillslope scale. These variations are poorly understood and should be a significant area for future research.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The current study attempts to identify differences in factors influencing soil erodibility in areas under pineapple production (traffic, ridge and furrow areas) and uncultivated natural vegetation. The key question addressed by this study as stated in Chapter 1 is: "What effect does pineapple cultivation have on the factors affecting soil erodibility of representative soils in the pineapple growing regions of Bathurst, Eastern Cape?". The goal of the thesis was thus to quantify the impact of pineapple cultivation on the factors influencing soil erodibility in the Glenrosa and Oakleaf soil forms.

The results illustrated a number of interesting trends which suggest that pineapple cultivation practices lead to increased soil erodibility. The discussion of the variations in factors controlling erodibility between the four sample sites indicated two basic processes which result in a higher susceptibility to erosion in the pineapple lands. The loosening-up process which accompanies ridging increases the porosity and decreases the bulk density of the ridge soils. This increases the rate of infiltration and reduces the likelihood of runoff. However, although the potential for surface runoff is reduced, ridging also decreases the aggregate stability of the soil which increases its erodibility. The second process is a consequence of compaction. In the traffic area adjacent to the pineapple lands and the pineapple furrows, vehicular and foot traffic compact the soil, reducing porosity and increasing bulk density. Infiltration rates are reduced in these areas, possibly leading to an increase in surface runoff and a greater soil erosion hazard than that found in undisturbed soils under natural vegetation.

An analysis of the variations in soil erodibility controlling factors within the sample sites attempted to identify where the greatest susceptibility to erosion was in the pineapple lands. Although variations in a number of factors influencing erodibility suggest the footslope areas of the Glenrosa soil form demonstrate a lower erodibility relative to the upslope areas, many of the results were contrary to expectations, illustrating the complexity and multiplicity of the soil erodibility phenomenon.

The results obtained tend to support the current recommendation of the Department of Agriculture and Water Supply whereby placing pineapple residue (plok) in the furrows is encouraged (Denyer, 1984). Placing mulch in the pineapple furrows will act as a physical obstruction to runoff and therefore reduce flow rates. Pineapple mulch would also increase the organic content of the soil and therefore indirectly reduce the effects of pineapple cultivation on soil erodibility. Organic content is one of the easiest factors influencing soil erodibility to manage and has a substantial impact on other factors influencing soil erodibility, for example bulk density, aggregate stability and shear strength. Incorporation of organic matter into the soil through time would possibly alleviate the negative effects of cultivation on soil erodibility. Aggregate stability would improve, infiltration rates would increase while bulk density would decrease. The water absorbtion capacity of the soil would therefore increase, reducing the amount and rate of runoff in the furrows. This, in turn, would reduce the likelihood of excessive soil loss and lower the soil erosion hazard in the pineapple lands.

A number of areas requiring additional research have been identified as a direct result of this study. For example, an investigation into the types of clay (kaolinites, illites or smectites) that occur in the pineapple lands would yield an improved understanding of the shrink and swell properties of soils and the relationship of clay content to aggregate stability.

A more detailed analysis of the chemical factors influencing soil erodibility is also advised. The present chemical analysis was limited by time as well as financial constraints, but a larger sample size as well as an investigation into other aspects of soil chemistry, such as the sodium adsorption ratio, would result in a better understanding of the differences in soil erodibility between different sites since the sodium adsorption ratio is related to the dispersiveness of soils (Morgan, 1986).

A more detailed investigation into the relationships between the factors affecting soil erodibility would also be beneficial in improving current knowledge of the processes which occur to either increase or decrease erodibility.

It must be realized, however, that soil erodibility is a dynamic rather than a static control on soil erosion. As yet, a comprehensive method for measuring or indexing the temporal variations has not yet been developed. Seasonal variations do occur in factors influencing soil erodibility (such as soil moisture, bulk density and shear strength amongst others) and these variations will have a major impact on the erodibility of the soil at different times of the year. Temporal variations in soil erodibility appear to be an important field of research that requires further investigation.

To maximise the research benefits, it is also suggested that an area should be investigated prior to pineapple cultivation and then, at regular intervals, after the initiation of pineapple production. This would facilitate a comparison of the soil properties pre- and post-cultivation. This would be preferable to comparing the soil characteristics of a cultivated soil to those in a reference natural vegetation.

If possible, the study should be duplicated on other soil forms with different natural soil characteristics. The optimum would be a situation in which the factors influencing soil erodibility had been identified and measured in all the major soil forms in the pineapple-growing regions.

Finally, another recommendation for future research is that the study be augmented with soil loss data. Erosion data could be compared to the data collected on the factors influencing soil erodibility. This would allow a soil erodibility index to be developed for the pineapple lands using a step-wise multivariate regression approach. A multivariate analysis is essential to test the interrelationships between different soil characteristics. A soil erodibility nomograph for pineapple lands is another possibility for future research.

It can be concluded that the study has quantified the effect of pineapple cultivation on several important factors controlling soil erodibility and thus improved current understanding of the processes affecting soil erodibility in the pineapple growing regions of Bathurst.

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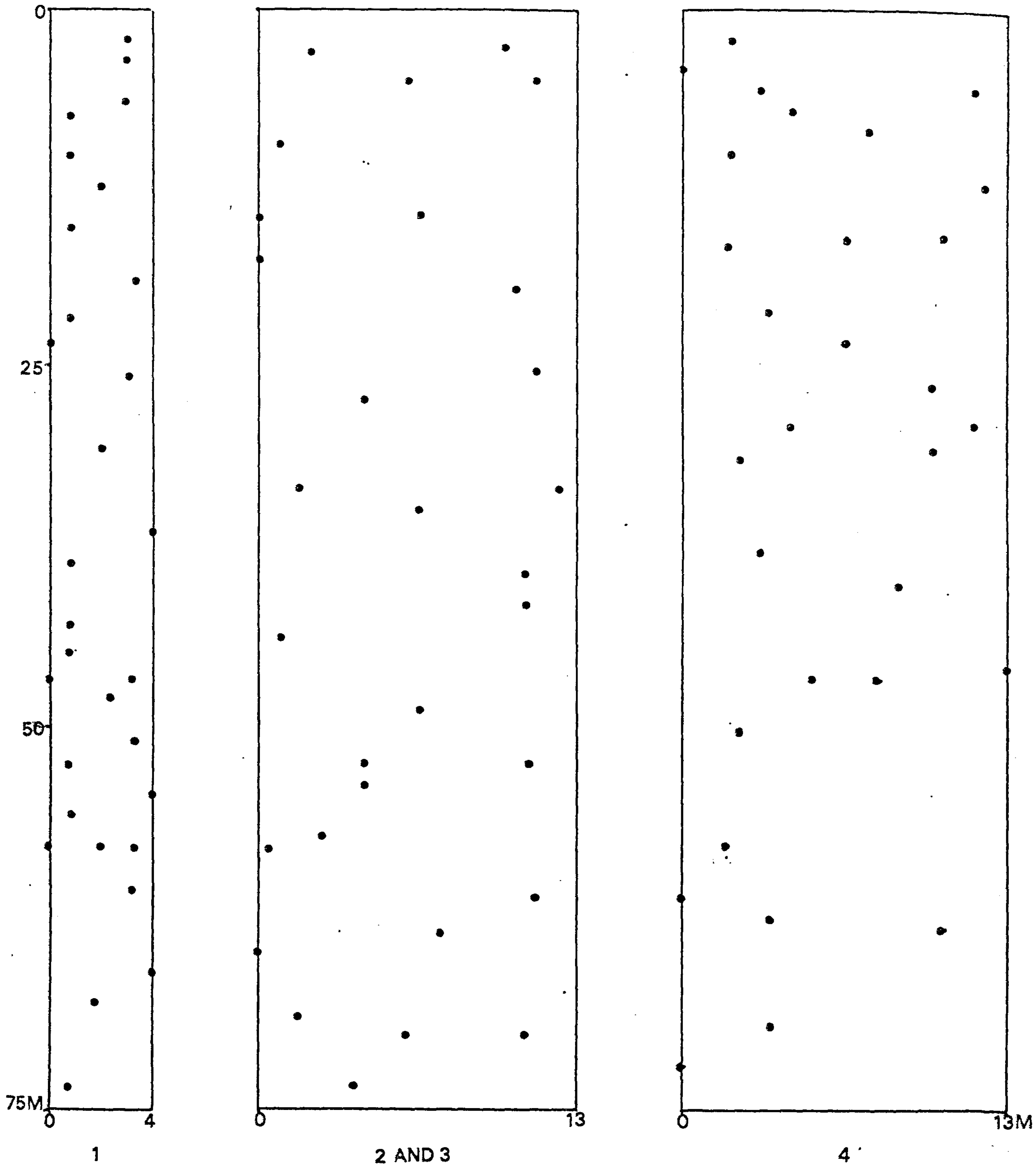
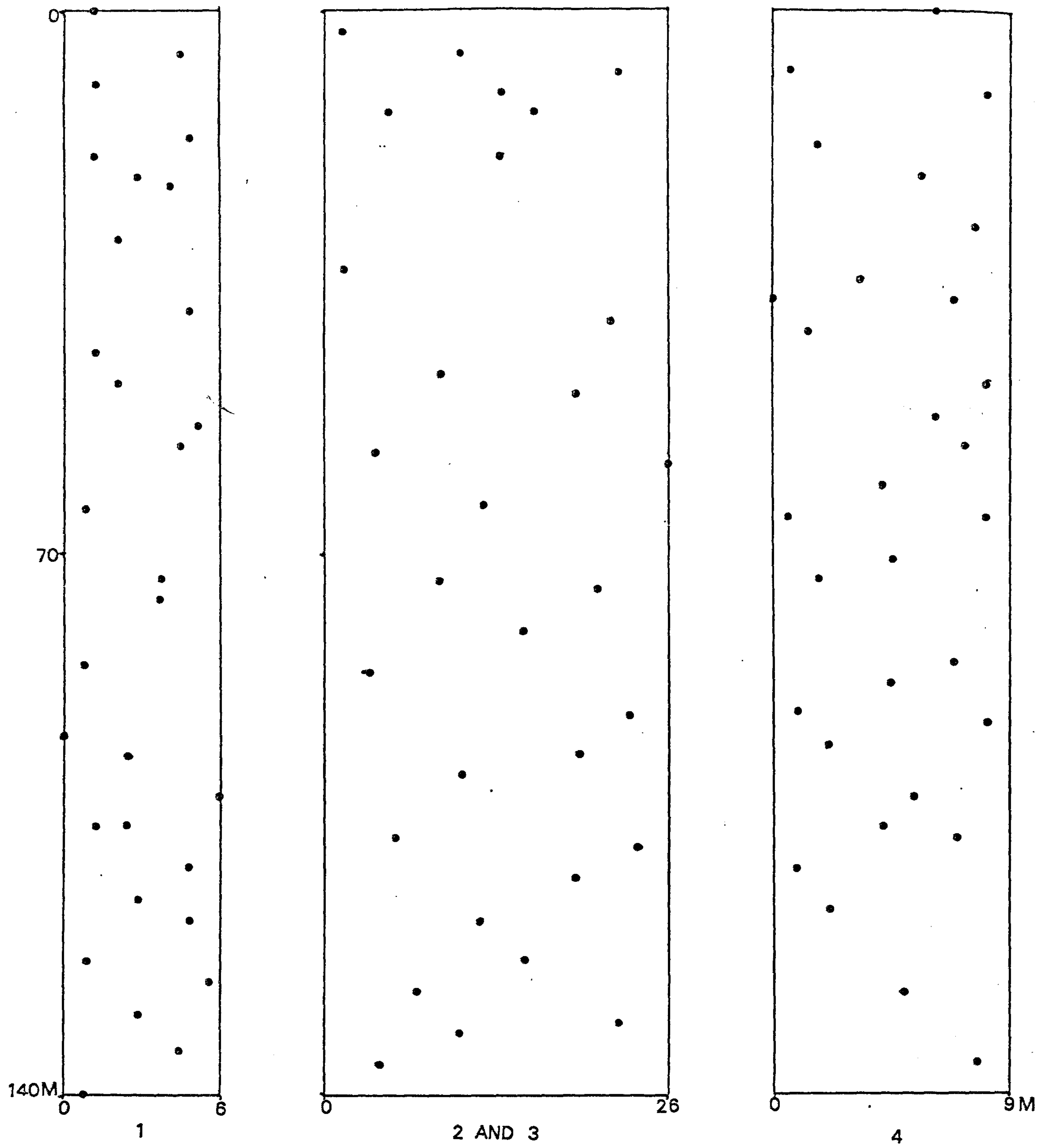
APPENDIX A
RANDOM SAMPLE POINTS



KEY

1. TRAFFIC AREA ADJACENT TO PINEAPPLE LANDS
2. PINEAPPLE RIDGE
3. PINEAPPLE FURROW
4. UNDISTURBED SOIL UNDER NATURAL VEGETATION

GLENROSA SOIL FORM



KEY

1. TRAFFIC AREA ADJACENT TO PINEAPPLE LANDS
2. PINEAPPLE RIDGE
3. PINEAPPLE FURROW
4. UNDISTURBED SOIL UNDER NATURAL VEGETATION

OAKLEAF SOIL FORM

APPENDIX B

SOIL PROFILE DESCRIPTIONS

GLENROSA PINEAPPLE LANDS

Farm:	Rosslyn
Vegetation/Land use:	Pineapple cultivation
Erosion:	Kind - Sheet
	Severity - Moderate
Surface rocks:	Slight
Slope/Aspect:	Approximately 4°/NE
Topography:	Footslope
Soil Form:	**Glenrosa**
Soil Family:	**Kilspindie**
Number:	**1121**

A HORIZON

Depth:	0 -30 cm
Moisture:	Moist
Colour:	10YR 3/3 (dark brown)
Mottling:	No mottling apparent
Texture:	Sandy loam
Structure:	Grade - single grained
	Size - fine
	Type - apedal
Consistence:	Moist - loose
Coarse fragments:	Subrounded - <20 mm
	Abundance - few (<15%)
Cutans:	No cutans apparent
Lime:	Negative
Water absorption:	Moderate
Transition:	Distinctness - clear
	Topography - smooth
Diagnostic horizon:	**Orthic A horizon**

B HORIZON

Depth:	30 - 65 mm
Moisture:	Moist
Colour:	5YR 3/4 (dark reddish brown)
Mottling:	Contrast - distinct
	Abundance - many (>20% of exposed surface)
	Size - medium (5 - 15 mm in diameter)
Texture:	Sandy loam
Structure:	Grade - moderate
	Size - fine
	Type - blocky subangular
Consistence:	Moist - slightly firm
Coarse fragments:	Subrounded - 75 - 250 mm
	Abundance - many (15 -50%)
Cutans:	Abundance - common
	Distinctness - prominent
	Location - throughout soil
Lime:	Negative
Water absorption:	Moderate
Diagnostic horizon:	**Lithocutanic B horizon**
Comments:	- A horizon not bleached
	- Lithocutanic B horizon merges into underlying weathered rock
	- B_1 horizon not hard
	- Signs of wetness in B_1 horizon
	- Non-calcareous B horizon

GLENROSA NATURAL VEGETATION

Farm:	Rosslyn
Vegetation/Land use:	Trees and grass
Erosion:	No erosion apparent
Surface rocks:	Moderate
Slope/Aspect:	Approximately 4°/NE
Topography:	Footslope
Soil Form:	**Glenrosa**
Soil Family:	**Kilspindie**
Number:	**1121**

A HORIZON

Depth:	0 -15 cm
Moisture:	Dry
Colour:	10YR 3/4 (dark yellowish brown)
Mottling:	No mottling apparent
Texture:	Sandy loam
Structure:	Grade - single grained
	Size - fine
	Type - apedal
Consistence:	Dry - slightly hard
Coarse fragments:	Subrounded - <20 mm
	Abundance - few
Cutans:	No cutans apparent
Lime:	Negative
Water absorption:	Rapid
Transition:	Distinctness - gradual
	Topography - smooth
Diagnostic horizon:	**Orthic A horizon**

B HORIZON

Depth:	15 - 58 cm
Moisture:	Moist
Colour:	5YR 3/4 (dark reddish brown)
Mottling:	Contrast - distinct
	Abundance - common (2 -20% of exposed surface)
	Size - medium (5 -15 mm in diameter)
Texture:	Sandy loam
Structure:	Grade - moderate
	Size - fine
	Type - blocky subangular
Consistence:	Moist - slightly hard
Coarse fragments:	Subrounded (75 - 250 mm)
	Abundance - many (15 - 50%)
Cutans:	Abundance - common
	Distinctness - prominent
	Location - throughout soil
Lime:	Negative
Water absorption:	Moderate
Diagnostic horizon:	**Lithocutanic B horizon**
Comments:	- A horizon not bleached
	- Lithocutanic B horizon merges into underlying weathered rock
	- B_1 horizon not hard
	- Signs of wetness in the B_1 horizon
	- Non-calcareous B horizon

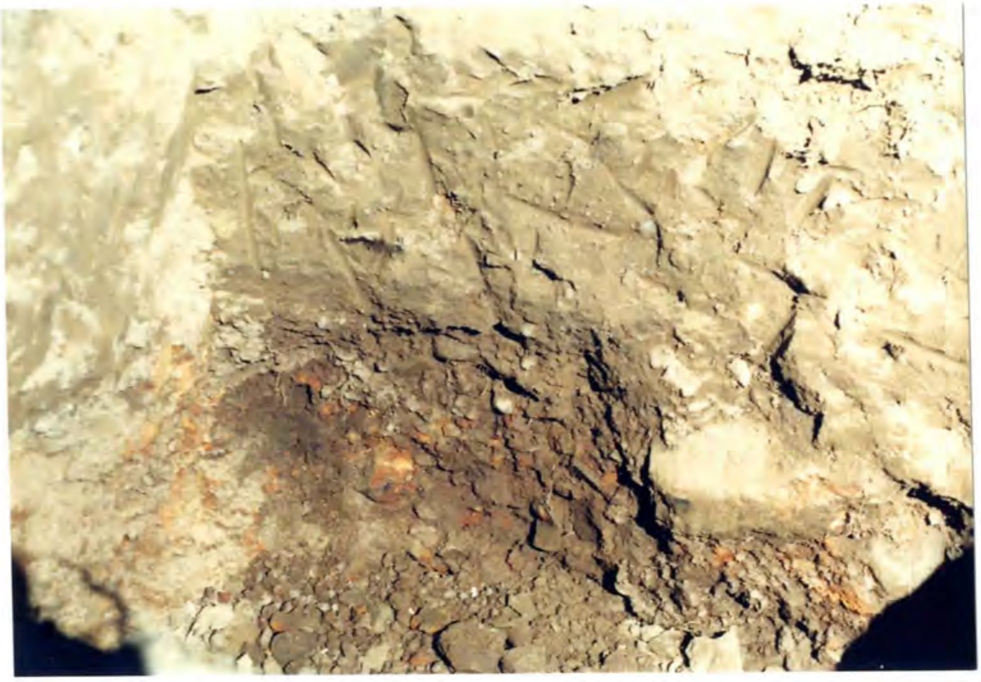


FIGURE B.1: Soil profile in the pineapple lands of the Glenrosa soil form

FIGURE B.2: Soil profile in the natural vegetation of the Glenrosa soil form

OAKLEAF PINEAPPLE LANDS

Farm:	Rosslyn
Vegetation/Land use:	Pineapple cultivation
Erosion:	Kind - Sheet
	Severity - Moderate
Surface Rocks:	Slight
Slope/Aspect:	Approximately 3°/SW
Topography:	Footslope
Soil form:	**Oakleaf**
Soil family:	**Ritchie**
Number:	**1110**

A HORIZON

Depth:	0 - 15 cm
Moisture:	Moist
Colour:	2.5Y 3/2 (very dark greyish brown)
Mottling:	No mottles apparent
Texture:	Sandy clay loam
Structure:	Grade - weak
	Size - fine
	Type - granular
Consistence:	Moist - friable
Coarse fragments:	None apparent
Cutans:	None apparent
Lime:	Negative
Water absorption:	Rapid
Transition:	Distinctiveness - Gradual
	Topography - Smooth
Diagnostic horizon:	**Orthic A horizon**

B HORIZON

Depth:	15 - 70 cm
Moisture:	Moist
Colour:	10YR 3/4 (dark yellowish brown)
Mottling:	Contrast - faint
	Abundance - few (<2%)
	Size - fine (>5 mm in diameter)
Texture:	Sandy clay loam
Structure:	Grade - moderate
	Size - medium
	Type - blocky subangular
Consistence:	Moist - slightly firm
Coarse fragments:	Subrounded - <20 mm
	Abundance - few (<15%)
Cutans:	Abundance - common
	Distinctness - faint
	Location - throughout soil
Lime:	Negative
Water absorption:	Rapid
Diagnostic horizon:	**Neocutanic B horizon**
Comments:	- A horizon not bleached
	- B horizon is non-uniform in colour by virtue of cutans
	- Non-red B horizon
	- Non-luvic B horizon

OAKLEAF NATURAL VEGETATION

Farm:	Rosslyn
Vegetation/Land use:	Trees and grass
Erosion:	No erosion apparent
Surface rocks:	Slight
Slope/Aspect:	Approximately 2° 30'/SW
Topography:	Footslope
Soil form:	**Oakleaf**
Soil family:	**Ritchie**
Number:	**1110**

A HORIZON

Depth:	0 - 20 cm
Moisture:	Dry
Colour:	2.5YR 3/2 (very dark greyish brown)
Mottling:	No mottling apparent
Texture:	Sandy clay loam
Structure:	Grade - moderate
	Size - fine
	Type - blocky subangular
Consistence:	Dry - slightly hard
Coarse fragments:	Subrounded - <20 mm
	Abundance - few (<15%)
Cutans:	No cutans apparent
Lime:	Negative
Water absorption:	Rapid
Transition:	Distinctness - gradual
	Topography - smooth
Diagnostic horizon:	**Orthic A horizon**

B HORIZON

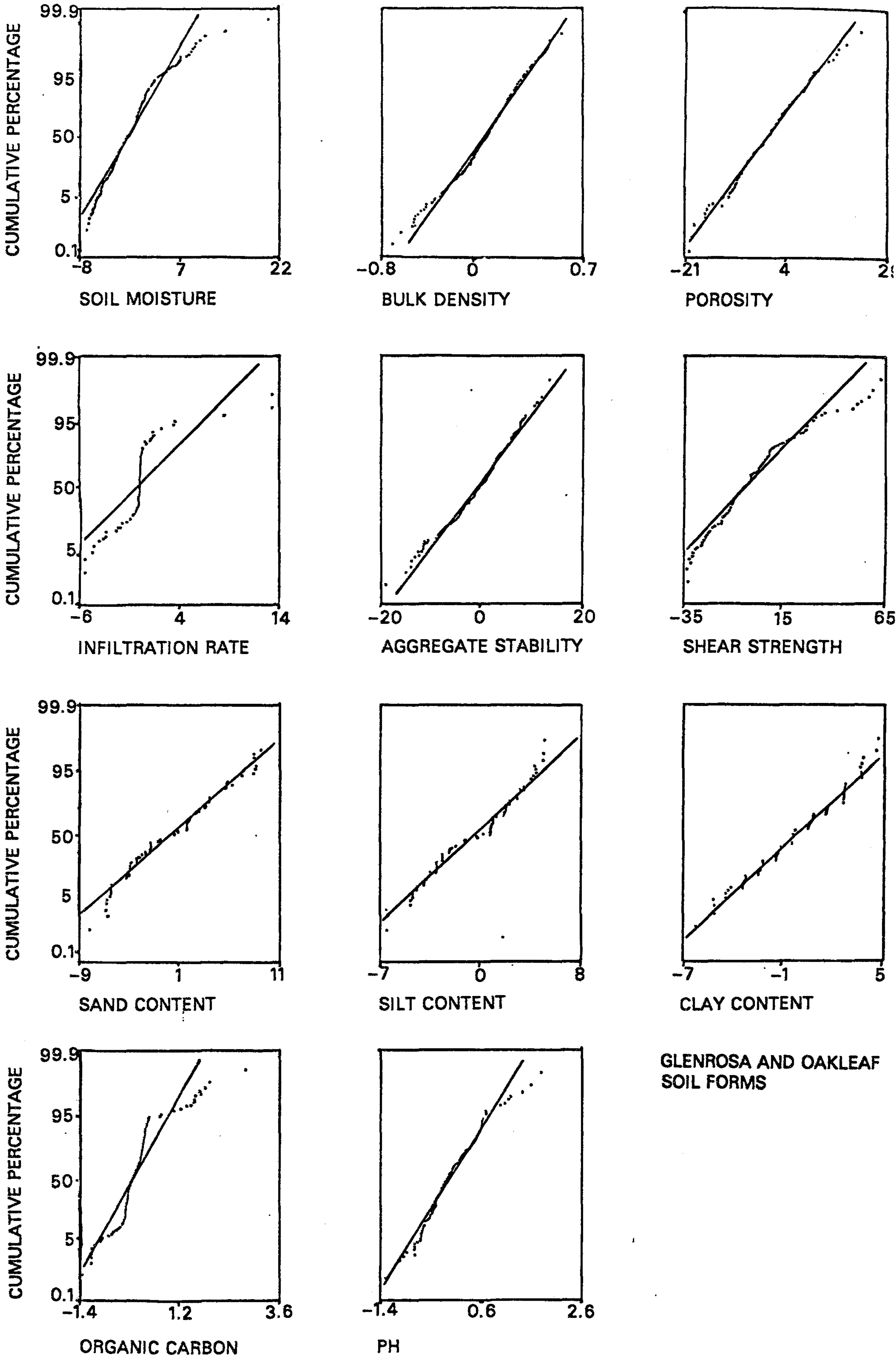
Depth:	20 - 60 cm
Moisture:	Dry
Colour:	10YR 3/3 (dark brown)
Mottling:	Contrast - faint
	Abundance - few (<2%)
	Size - fine (<5 mm in diameter)
Texture:	Sandy clay loam
Structure:	Grade - moderate
	Size - medium
	Type - blocky subangular
Consistence:	Dry - slightly hard
Coarse fragments:	Subrounded - <20 mm
	Few (<15%)
Cutans:	Abundance - few
	Distinctness - faint
	Location - throughout soil
Lime:	Negative
Water absorption:	Rapid
Diagnostic horizon:	**Neocutanic B horizon**
Comments:	- A horizon not bleached
	- B horizon non-uniform in colour by virtue of cutans
	- Non-red B horizon
	- Non-luvic B horizon

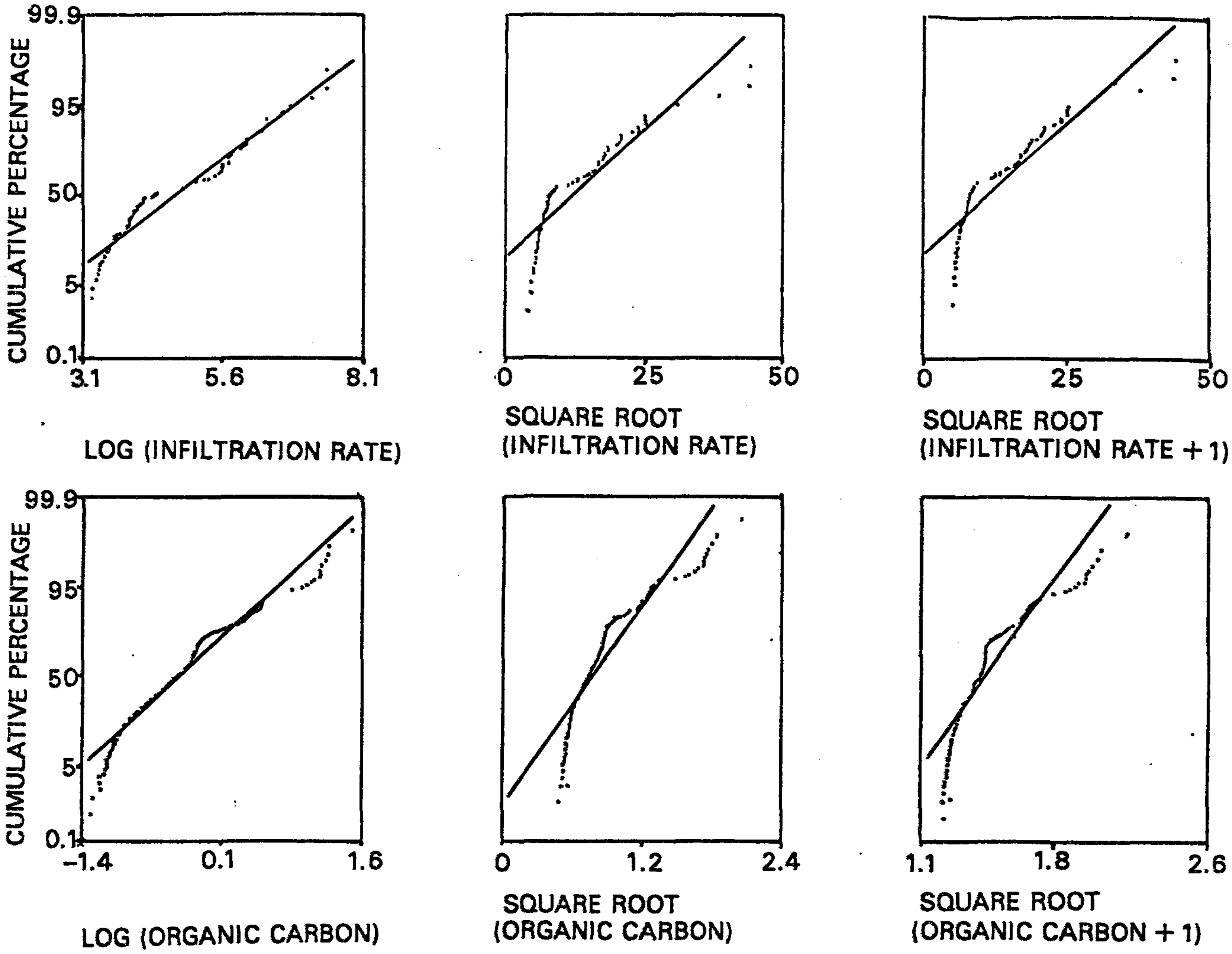
FIGURE B.3: Soil profile in the pineapple lands of the Oakleaf soil form

FIGURE B.4: Soil profile in the natural vegetation of the Oakleaf soil form

APPENDIX C

NORMAL PROBABILITY PLOTS OF RESIDUALS


CUMULATIVE PERCENTAGE
99.9
95
50
5
0.1
-8
7
22
SOIL MOISTURE
-0.8
0
0.7
BULK DENSITY
-21
4
POROSITY
-6
4
14
INFILTRATION RATE
-20
0
20
AGGREGATE STABILITY
-35
15
65
SHEAR STRENGTH
-9
1
11
SAND CONTENT
-7
0
8
SILT CONTENT
-7
-1
5
CLAY CONTENT
-1.4
1.2
3.6
ORGANIC CARBON
-1.4
0.6
2.6
PH
GLENROSA AND OAKLEAF
SOIL FORMS



GLENROSA AND OAKLEAF SOIL FORMS

APPENDIX D

REQUIREMENTS FOR USING ANALYSIS OF VARIANCE

TABLE D.1: Requirements for using Analysis of Variance - Glenrosa and Oakleaf soil forms

SOIL CHARACTERISTIC	A	B	C	D	
Soil Moisture	Y	Y	Y	1.110E-16	N
Bulk Density	Y	Y	Y	1.476E-12	N
Porosity	Y	Y	Y	0.076	Y
Infiltration	Y	Y	N	0.000	N
Agg. Stability	Y	Y	Y	1.185E-5	N
Shear Strength	Y	Y	Y	6.994E-14	N
% Sand	Y	Y	Y	0.308	Y
% Silt	Y	Y	Y	0.176	Y
% Clay	Y	Y	Y	0.089	Y
Organic Carbon	Y	Y	N	0.000	N
pH	Y	Y	Y	0.043	N

where

A = data randomly and independantly selected

B = data in interval form

C = data normally distributed (based on the normal probability plots)

D = Bartlett's P value for homogeneity of variances (the assumption is satisfied if $P > 0.05$)

Y = assumption satisfied

N = assumption not satisfied

Based on these requirements, infiltration rate and organic carbon data were transformed:

SOIL CHARACTERISTIC	A	B	C	D	
Log(Infiltration)	Y	Y	Y	1.593E-9	N
Log(Organic carbon)	Y	Y	Y	1.715E-5	N

TABLE D.2: Requirements for Analysis of Variance - Glenrosa soil form

SOIL CHARACTERISTIC	A	B	C	D	
Soil Moisture	Y	Y	Y	3.385E-11	N
Bulk Density	Y	Y	Y	0.016	N
Porosity	Y	Y	Y	0.016	N
Infiltration	Y	Y	N	4.441E-16	N
Agg. Stability	Y	Y	Y	1.443E-3	N
Shear Strength	Y	Y	Y	2.076E-14	N
% Sand	Y	Y	Y	0.276	Y
% Silt	Y	Y	Y	3.986E-4	N
% Clay	Y	Y	Y	0.472	Y
Organic Carbon	Y	Y	N	0.000	N
pH	Y	Y	Y	5.986E-10	N

where

A = data randomly and independantly selected

B = data in interval form

C = data normally distributed (based on the normal probability plots)

D = Bartlett's P value for homogeneity of variances (assumption is satisfied if $P > 0.05$)

Y = assumption satisfied

N = assumption not satisfied

Based on these requirements, infiltration rate and organic carbon data were transformed:

SOIL CHARACTERISTIC	A	B	C	D	
Log(Infiltration)	Y	Y	Y	9.201E-8	N
Log(Organic carbon)	Y	Y	Y	2.231E-4	N

TABLE D.3: Requirements for using Analysis of Variance - Oakleaf soil form

SOIL CHARACTERISTIC	A	B	C	D	
Soil Moisture	Y	Y	Y	1.110E-16	N
Bulk Density	Y	Y	Y	2.316E-5	N
Porosity	Y	Y	Y	0.584	Y
Infiltration	Y	Y	N	0.000	N
Agg. Stability	Y	Y	Y	0.045	N
Shear Strength	Y	Y	Y	4.243E-6	N
% Sand	Y	Y	Y	9.765E-4	N
% Silt	Y	Y	Y	0.043	N
% Clay	Y	Y	Y	0.340	Y
Organic Carbon	Y	Y	N	0.000	N
pH	Y	Y	Y	0.252	Y

where

A = data randomly and independantly selected

B = data in interval form

C = data normally distributed (based on normal probability plots)

D = Bartlett's P value for homogeneity of variances (assumption is satisfied if $P > 0.05$)

Y = assumption satisfied

N = assumption not satisfied

Based on these requirements, infiltration rate and organic carbon data were transformed:

SOIL CHARACTERISTIC	A	B	C	D	
Log(Infiltration)	Y	Y	Y	2.093E-3	N
Log(Organic carbon)	Y	Y	Y	1.110E-16	N

APPENDIX E

RESULTS OF THE CORRELATION ANALYSIS

TABLE E.1: Results of the Correlation Analysis - Glenrosa and Oakleaf soil forms

	SM	BD	P	IR	AS	SS
SM	1.000 1.000 480	-0.088 0.008 480	0.155 0.024 240	-0.097 0.009 80	0.214 0.046 240	-0.098 0.010 240
BD	-0.088 0.008 480	1.000 1.000 480	**-0.903** **0.815** **240**	-0.565 0.319 80	-0.460 0.212 240	0.217 0.047 240
P	0.155 0.024 240	**-0.903** **0.815** **240**	1.000 1.000 240	0.444 0.197 80	0.330 0.109 240	-0.261 0.068 240
IR	-0.097 0.009 80	-0.565 0.319 80	0.253 0.064 80	1.000 1.000 80	0.399 0.159 80	-0.071 0.005 80
AS	0.214 0.046 240	-0.460 0.212 240	0.330 0.109 240	0.399 0.159 80	1.000 1.000 240	-0.057 0.003 240
SS	-0.098 0.010 240	0.217 0.047 240	-0.261 0.068 240	-0.071 0.005 80	-0.057 0.003 240	1.000 1.000 240
%SA	0.153 0.023 120	0.010 0.000 120	0.012 0.000 120	0.253 0.064 80	0.260 0.068 120	0.086 0.007 12O
%SI	0.018 0.000 120	-0.465 0.216 120	0.282 0.008 120	0.242 0.059 80	0.322 0.104 120	-0.035 0.001 120
%C	-0.183 0.033 120	0.289 0.084 120	-0.204 0.042 120	0.463 0.214 80	-0.508 0.258 120	-0.079 0.006 120
OC	0.104 0.011 240	**-0.652** **0.425** **240**	0.473 0.224 240	0.589 0.347 80	0.534 0.285 240	-0.010 0.000 240
PH	0.206 0.042 240	-0.521 0.271 240	0.382 0.146 240	0.423 0.179 80	0.606 0.367 240	0.192 0.037 240

	%SA	%SI	%C	OC	PH
SM	0.153 0.023 120	0.018 0.000 120	-0.183 0.033 120	0.104 0.011 240	0.206 0.042 240
BD	0.010 0.000 120	-0.465 0.216 120	0.289 0.084 120	**-0.652** **0.425** **240**	-0.460 0.212 240
P	0.012 0.000 120	0.282 0.008 120	-0.204 0.042 120	0.473 0.224 240	0.382 0.146 240
IR	0.253 0.064 80	0.242 0.059 80	-0.463 0.214 80	0.589 0.347 80	0.423 0.179 80
AS	0.260 0.068 120	0.322 0.104 120	-0.508 0.258 120	0.534 0.285 240	0.606 0.367 240
SS	0.086 0.007 120	-0.035 0.001 120	-0.079 0.006 120	-0.010 0.000 240	0.192 0.037 240
%SA	1.000 1.000 120	-0.562 0.316 120	**-0.845** **0.714** **120**	0.245 0.060 120	0.403 0.162 120
%SI	-0.562 0.316 120	1.000 1.000 120	0.036 0.001 120	0.354 0.125 120	0.272 0.074 120
%C	**-0.845** **0.714** **120**	0.036 0.001 120	1.000 1.000 120	-0.521 0.271 120	**-0.662** **0.438** **120**
OC	0.245 0.060 120	0.354 0.125 120	-0.521 0.271 120	1.000 1.000 240	0.628 0.394 240
PH	0.403 0.162 120	0.272 0.074 120	**-0.662** **0.438** **120**	0.628 0.394 240	1.000 1.000 240

TABLE E.2: Results of the Correlation Analysis - Glenrosa soil form

	SM	BD	P	IR	AS	SS
SM	1.000 1.000 240	-0.444 0.197 240	0.409 0.167 120	0.194 0.038 40	0.447 0.200 120	-0.326 0.106 120
BD	-0.444 0.197 240	1.000 1.000 240	**-0.941** **0.885** **120**	-0.391 0.153 40	-0.409 0.167 120	0.234 0.055 120
P	0.409 0.167 120	**-0.941** **0.885** **120**	1.000 1.000 120	0.374 0.140 40	0.321 0.103 120	-0.262 0.069 120
IR	0.194 0.038 40	-0.391 0.153 40	0.374 0.140 40	1.000 1.000 40	0.356 0.127 40	-0.215 0.046 40
AS	0.447 0.200 120	-0.409 0.167 120	0.321 0.103 120	0.356 0.127 40	1.000 1.000 120	-0.118 0.014 120
SS	-0.326 0.106 120	0.234 0.055 120	-0.262 0.069 120	-0.215 0.046 40	-0.118 0.014 120	1.000 1.000 120
%SA	-0.001 0.000 60	-0.151 0.023 60	0.104 0.011 60	0.195 0.038 40	0.418 0.175 60	0.237 0.056 60
%SI	0.314 0.099 60	-0.290 0.084 60	0.255 0.065 60	0.411 0.169 40	0.199 0.040 60	-0.287 0.082 60
%C	-0.159 0.025 60	0.323 0.104 60	-0.258 0.067 60	-0.449 0.202 40	-0.556 0.309 60	-0.097 0.009 60
OC	0.409 0.167 120	-0.435 0.189 120	0.381 0.145 120	0.265 0.070 40	0.587 0.345 120	0.037 0.001 120
PH	0.377 0.142 120	-0.415 0.172 120	0.332 0.110 120	0.335 0.112 40	0.606 0.371 120	0.228 0.052 120

	%SA	%SI	%C	OC	PH
SM	-0.001 0.000 60	0.314 0.099 60	-0.159 0.025 60	0.409 0.167 120	0.377 0.142 120
BD	-0.151 0.023 60	-0.290 0.084 60	0.323 0.104 60	-0.435 0.189 120	-0.415 0.172 120
P	0.104 0.011 60	0.255 0.065 60	-0.258 0.067 60	0.381 0.145 120	0.332 0.110 120
IR	0.195 0.038 40	0.411 0.169 40	-0.449 0.202 40	0.265 0.070 40	0.335 0.112 40
AS	0.418 0.175 60	0.199 0.040 60	-0.556 0.309 60	0.587 0.345 120	0.606 0.371 120
SS	0.237 0.056 60	-0.287 0.082 60	-0.097 0.009 60	0.037 0.001 120	0.228 0.052 120
%SA	1.000 1.000 60	-0.413 0.171 60	**-0.855 0.731 60**	0.453 0.205 60	**0.667 0.445 60**
%SI	-0.413 0.171 60	1.000 1.000 60	-0.117 0.031 60	0.133 0.018 60	0.073 0.005 60
%C	**-0.855 0.731 60**	-0.117 0.031 60	1.000 1.000 60	-0.562 0.316 60	**-0.768 0.590 60**
OC	0.453 0.205 60	0.133 0.018 60	-0.562 0.316 60	1.000 1.000 120	0.609 0.371 120
PH	**0.667 0.445 60**	0.073 0.005 60	**-0.768 0.590 60**	0.609 0.371 120	1.000 1.000 120

TABLE E.3: Results of the Correlation Analysis - Oakleaf soil form

	SM	BD	P	IR	AS	SS
SM	1.000 1.000 240	0.144 0.021 240	-0.010 0.000 120	-0.069 0.005 40	-0.033 0.001 120	0.252 0.064 120
BD	0.144 0.021 240	1.000 1.000 240	**-0.881** **0.776** **120**	-0.631 0.398 40	-0.392 0.154 120	0.306 0.094 120
P	-0.010 0.000 120	**-0.881** **0.776** **120**	1.000 1.000 120	0.482 0.232 40	0.225 0.051 120	-0.316 0.100 120
IR	-0.069 0.005 40	-0.631 0.398 40	0.482 0.232 40	1.000 1.000 40	0.482 0.232 40	-0.080 0.006 40
AS	-0.033 0.001 120	-0.392 0.154 120	0.225 0.051 120	0.482 0.232 40	1.000 1.000 120	-0.008 0.000 120
SS	0.252 0.064 120	0.306 0.094 120	-0.316 0.100 120	-0.080 0.006 40	-0.008 0.000 120	1.000 1.000 120
%SA	0.140 0.020 60	-0.332 0.110 60	0.103 0.011 60	0.554 0.307 40	0.636 0.404 60	0.121 0.015 60
%SI	0.067 0.004 60	-0.360 0.130 60	0.319 0.102 60	0.152 0.023 40	0.165 0.027 60	0.007 0.000 60
%C	-0.150 0.023 60	0.455 0.207 60	-0.222 0.049 60	-0.604 0.365 40	**-0.662** **0.438** **60**	0.114 0.013 60
OC	-0.014 0.000 120	**-0.680** **0.462** **120**	0.444 0.197 120	**0.652** **0.425** **40**	0.471 0.222 120	-0.070 0.005 120
PH	0.024 0.001 120	-0.566 0.320 120	0.347 0.120 120	0.629 0.396 40	0.519 0.269 120	0.124 0.015 120

	%SA	%SI	%C	OC	PH
SM	0.140 0.020 60	0.067 0.004 60	-0.150 0.023 60	-0.014 0.000 120	0.024 0.001 120
BD	-0.332 0.110 60	-0.360 0.130 60	0.455 0.207 60	**-0.680** **0.462** **120**	-0.566 0.320 120
P	0.103 0.011 60	0.319 0.102 60	-0.222 0.049 60	0.444 0.197 120	0.347 0.120 120
IR	0.554 0.307 40	0.152 0.023 40	-0.604 0.365 40	**0.652** **0.425** **40**	0.629 0.396 40
AS	0.636 0.404 60	0.165 0.027 60	**-0.662** **0.438** **60**	0.471 0.222 120	0.519 0.269 120
SS	0.121 0.015 60	0.007 0.000 60	-0.114 0.013 60	-0.070 0.005 120	0.124 0.015 120
%SA	1.000 1.000 60	-0.103 0.011 60	**-0.941** **0.865** **60**	0.578 0.334 60	0.638 0.407 60
%SI	-0.103 0.011 60	1.000 1.000 60	0.231 0.053 60	0.307 0.094 60	0.362 0.131 60
%C	**-0.941** **0.885** **60**	-0.231 0.053 60	1.000 1.000 60	**-0.670** **0.449** **60**	**0.745** **0.555** **60**
OC	0.578 0.334 60	0.307 0.094 60	**-0.670** **0.449** **60**	1.000 1.000 120	**0.693** **0.480** **120**
PH	0.638 0.407 60	0.362 0.131 60	**0.745** **0.555** **60**	**0.693** **0.480** **120**	1.000 1.000 120

where 1.000 = r

1.000 = r^2

480 = N

SM = Soil moisture (% weight)

BD = Bulk density ($g.cm^{-3}$)

P = Porosity (% volume)

IR = Infiltration rate ($ml.minute^{-1}$)

AS = Aggregate stability

SS = Shear strength (KPa)

%SA = Sand content (%)

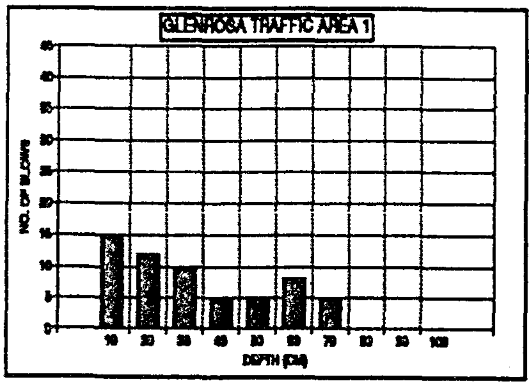
%SI = Silt content (%)

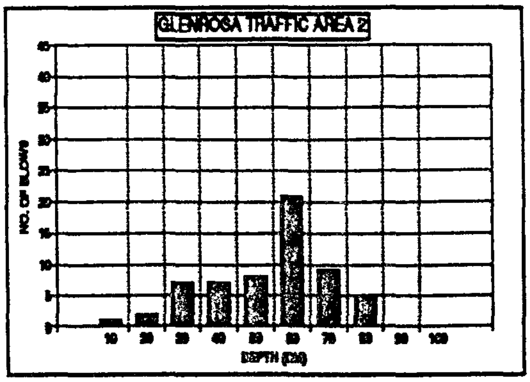
%C = Clay content (%)

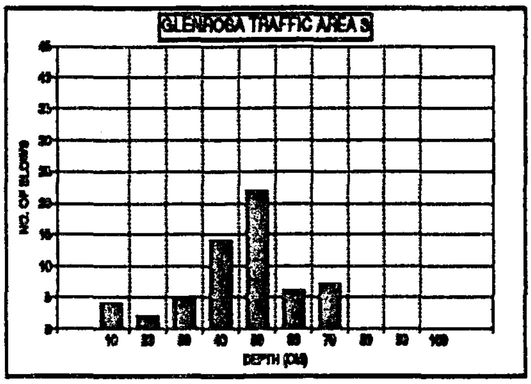
OC = Organic carbon (%)

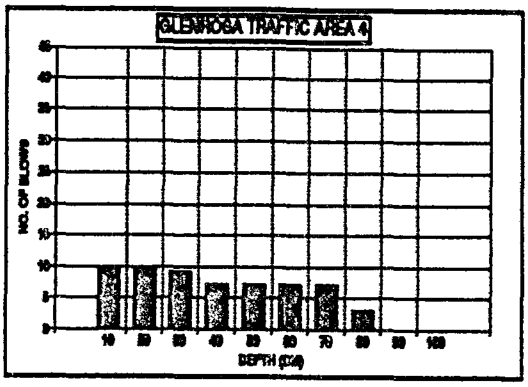
PH = pH (pH units)

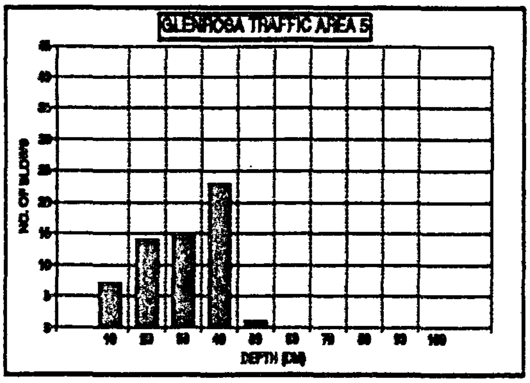
APPENDIX F
RESULTS OF THE PENETRABILITY TESTS

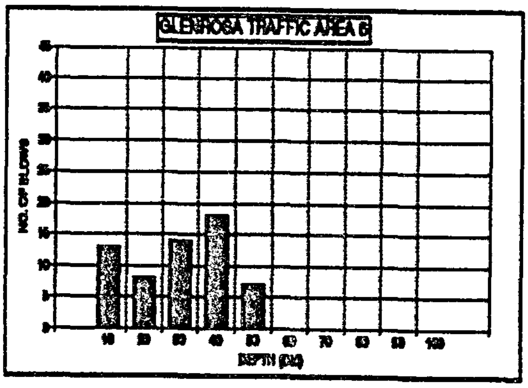

GLENROSA TRAFFIC AREA 1
NO. OF BLOWS
DEPTH (CM)

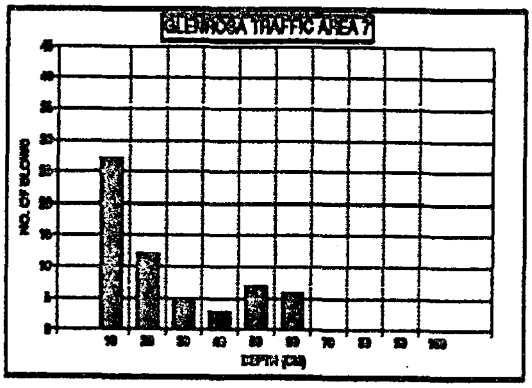

GLENROSA TRAFFIC AREA 2
NO. OF BLOWS
DEPTH (CM)

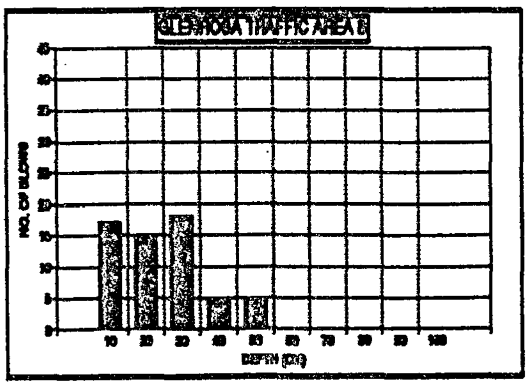

GLENROSA TRAFFIC AREA 3
NO. OF BLOWS
DEPTH (CM)

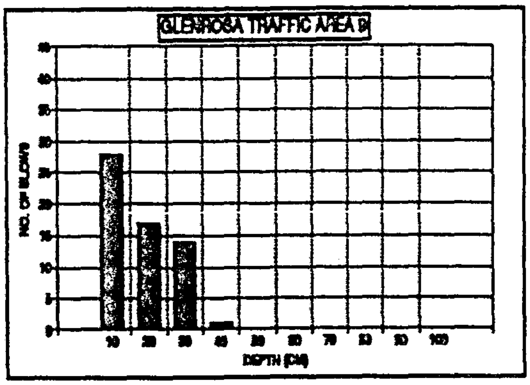

GLENROSA TRAFFIC AREA 4
NO. OF BLOWS
DEPTH (CM)

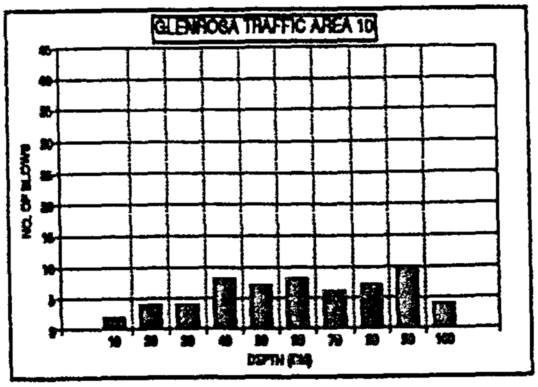

GLENROSA TRAFFIC AREA 5
NO. OF BLOWS
DEPTH (CM)

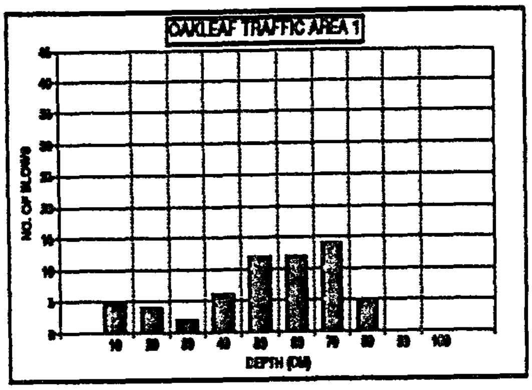

GLENROSA TRAFFIC AREA 6
NO. OF BLOWS
DEPTH (CM)

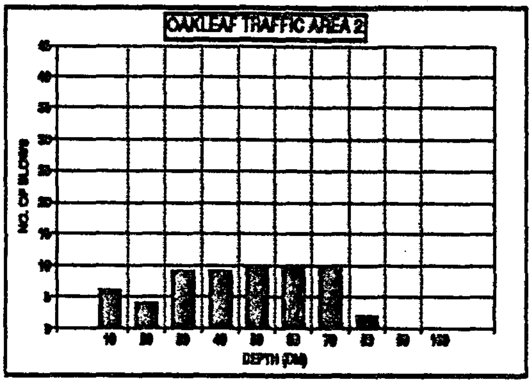

GLENROSA TRAFFIC AREA 7
NO. OF BLOWS
DEPTH (CM)

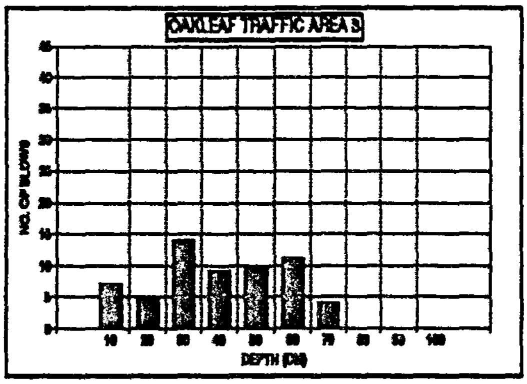

GLENROSA TRAFFIC AREA 8
NO. OF BLOWS
DEPTH (CM)

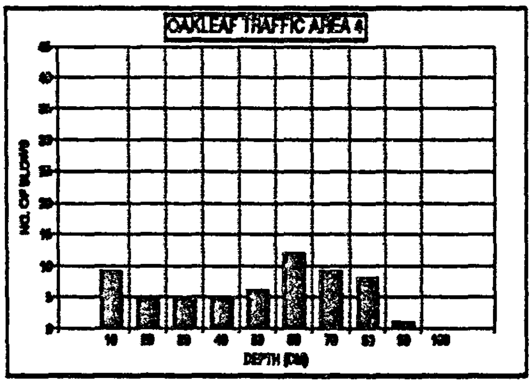

GLENROSA TRAFFIC AREA 9
NO. OF BLOWS
DEPTH (CM)

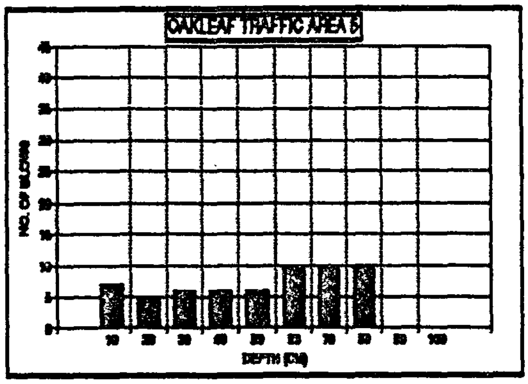

GLENROSA TRAFFIC AREA 10
NO. OF BLOWS
DEPTH (CM)

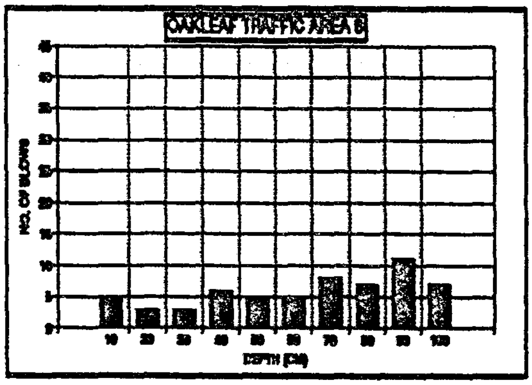

OAKLEAF TRAFFIC AREA 1
NO. OF BLOWS
DEPTH (CM)

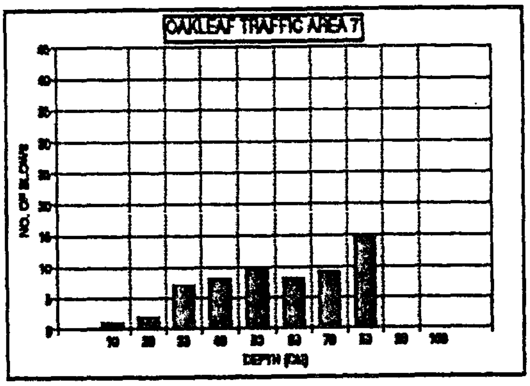

OAKLEAF TRAFFIC AREA 2
NO. OF BLOWS
DEPTH (CM)

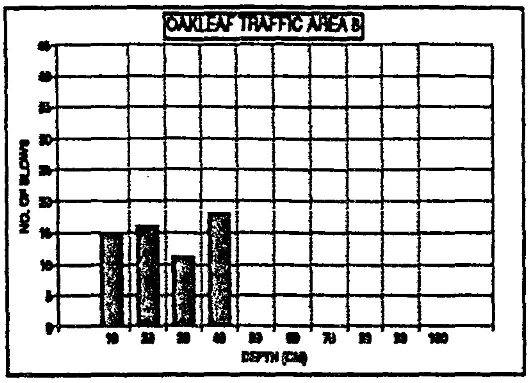

OAKLEAF TRAFFIC AREA 3
NO. OF BLOWS
DEPTH (CM)

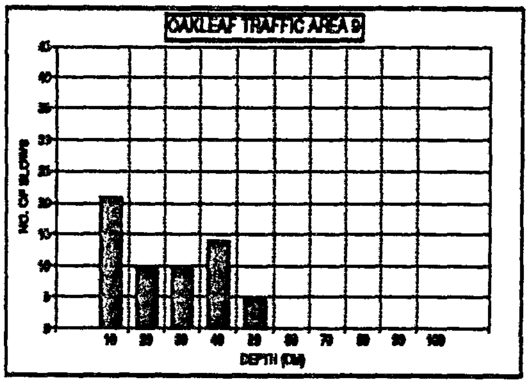

OAKLEAF TRAFFIC AREA 4
NO. OF BLOWS
DEPTH (CM)

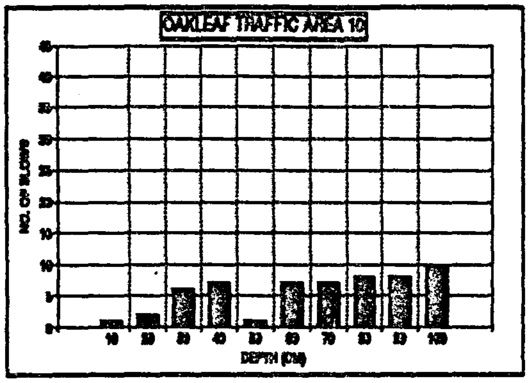

OAKLEAF TRAFFIC AREA 5
NO. OF BLOWS
DEPTH (CM)

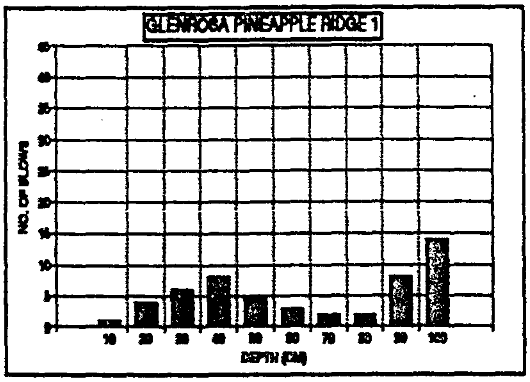

OAKLEAF TRAFFIC AREA 6
NO. OF BLOWS
DEPTH (CM)

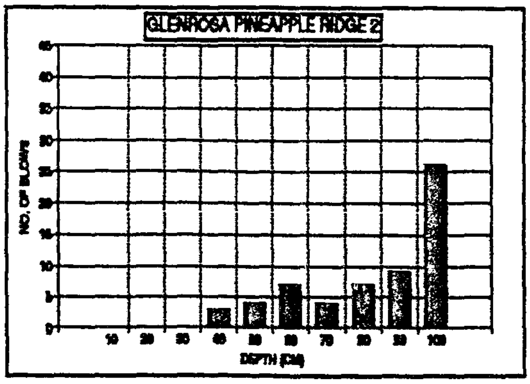

OAKLEAF TRAFFIC AREA 7
NO. OF BLOWS
DEPTH (CM)

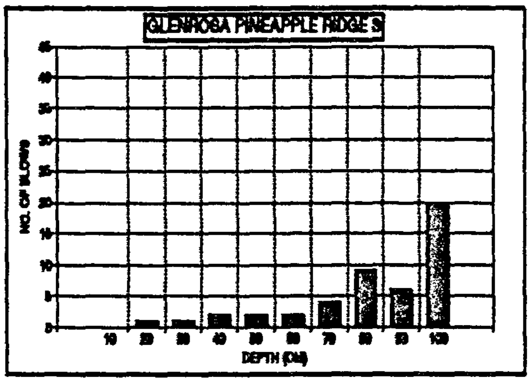

OAKLEAF TRAFFIC AREA 8
NO. OF BLOWS
DEPTH (CM)

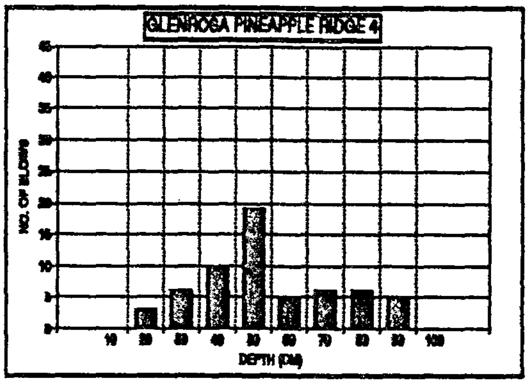

OAKLEAF TRAFFIC AREA 9
NO. OF BLOWS
DEPTH (CM)

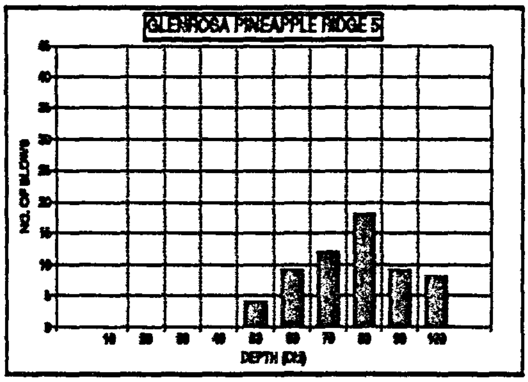

OAKLEAF TRAFFIC AREA 10
NO. OF BLOWS
DEPTH (CM)

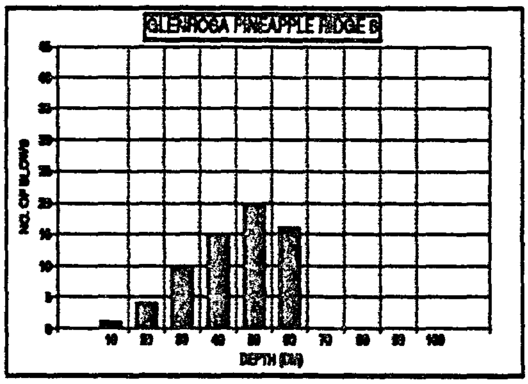

GLENROSA PINEAPPLE RIDGE 1
NO. OF BLOWS
DEPTH (CM)

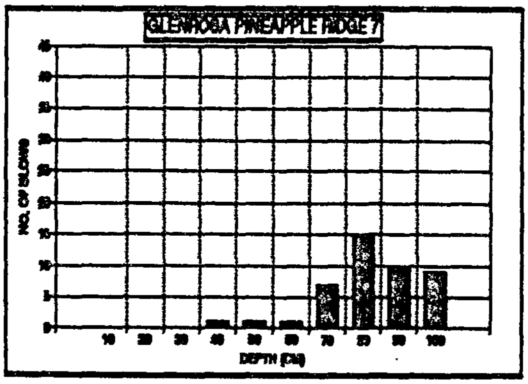

GLENROSA PINEAPPLE RIDGE 2
NO. OF BLOWS
DEPTH (CM)

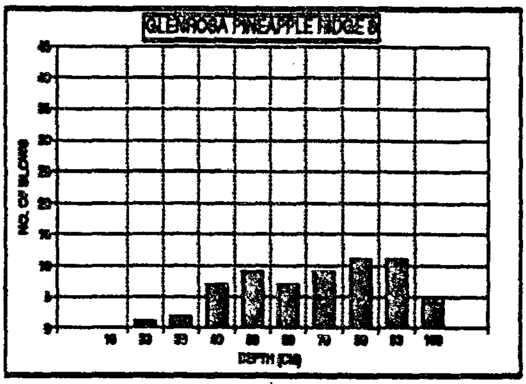

GLENROSA PINEAPPLE RIDGE 3
NO. OF BLOWS
DEPTH (CM)

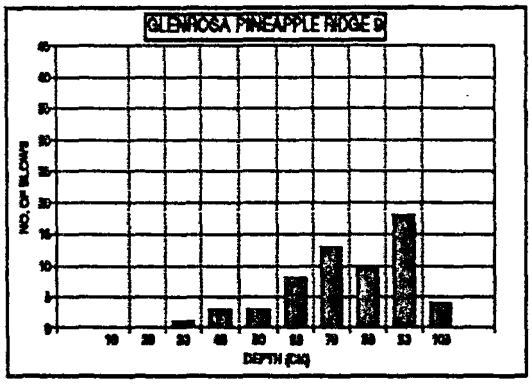

GLENROSA PINEAPPLE RIDGE 4
NO. OF BLOWS
DEPTH (CM)

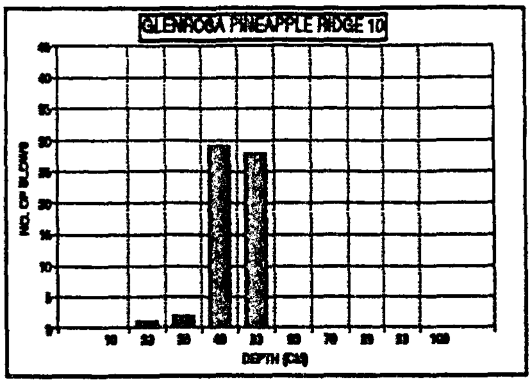

GLENROSA PINEAPPLE RIDGE 5
NO. OF BLOWS
DEPTH (CM)

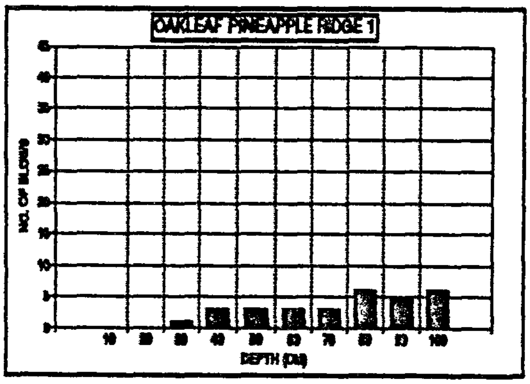

GLENROSA PINEAPPLE RIDGE 6
NO. OF BLOWS
DEPTH (CM)

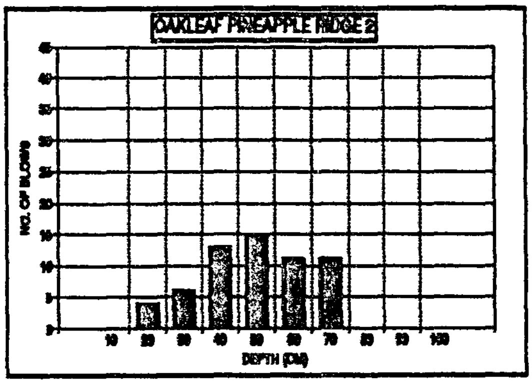

GLENROSA PINEAPPLE RIDGE 7
NO. OF BLOWS
DEPTH (CM)

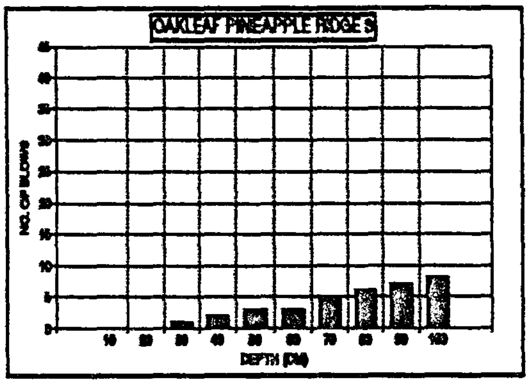

GLENROSA PINEAPPLE RIDGE 8
NO. OF BLOWS
DEPTH (CM)

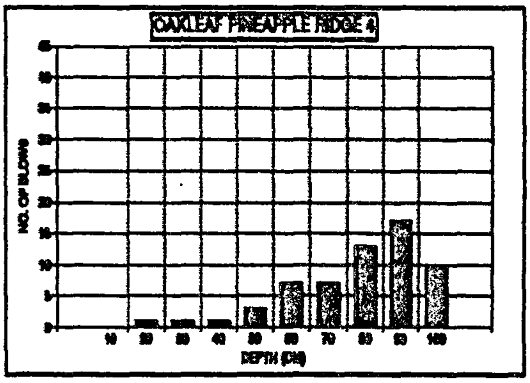

GLENROSA PINEAPPLE RIDGE 9
NO. OF BLOWS
DEPTH (CM)

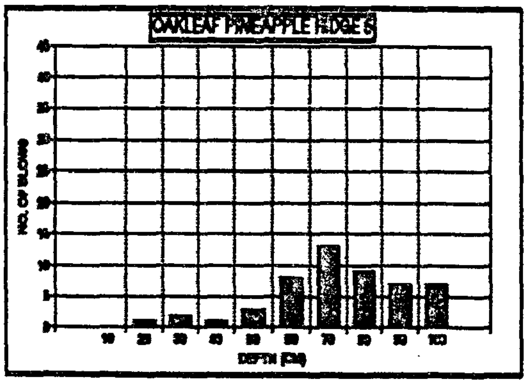

GLENROSA PINEAPPLE RIDGE 10
NO. OF BLOWS
DEPTH (CM)

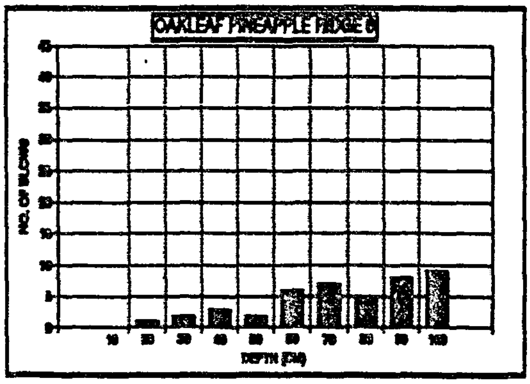

OAKLEAF PINEAPPLE RIDGE 1
NO. OF BLOWS
DEPTH (CM)

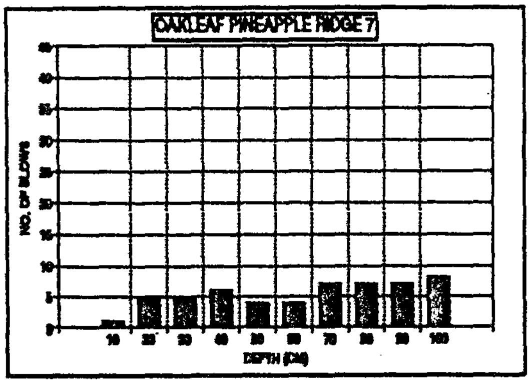

OAKLEAF PINEAPPLE RIDGE 2
NO. OF BLOWS
DEPTH (CM)

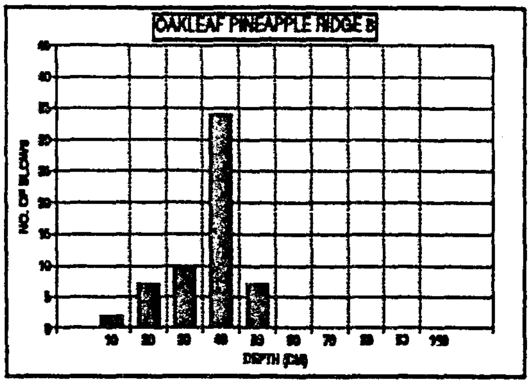

OAKLEAF PINEAPPLE RIDGE 3
NO. OF BLOWS
DEPTH (CM)

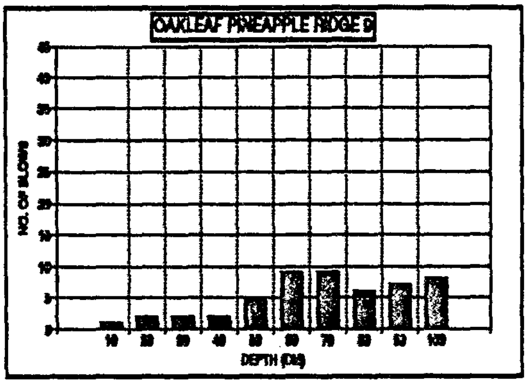

OAKLEAF PINEAPPLE RIDGE 4
NO. OF BLOWS
DEPTH (CM)

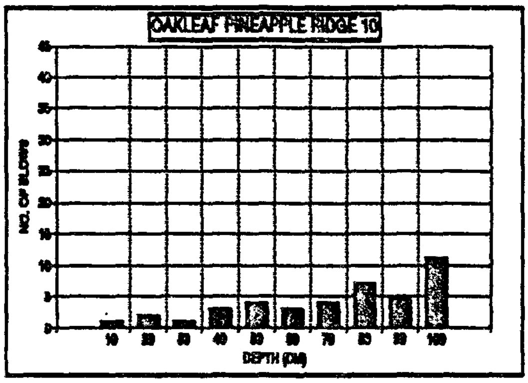

OAKLEAF PINEAPPLE RIDGE 5
NO. OF BLOWS
DEPTH (CM)

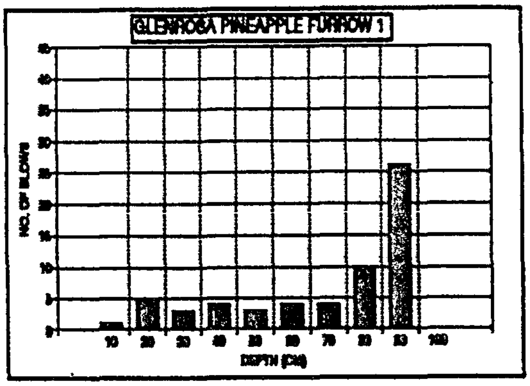

OAKLEAF PINEAPPLE RIDGE 6
NO. OF BLOWS
DEPTH (CM)

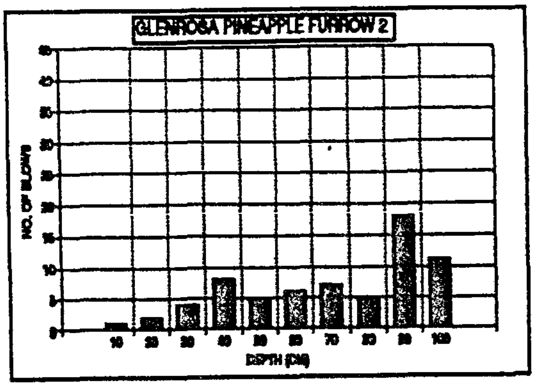

OAKLEAF PINEAPPLE RIDGE 7
NO. OF BLOWS
DEPTH (CM)

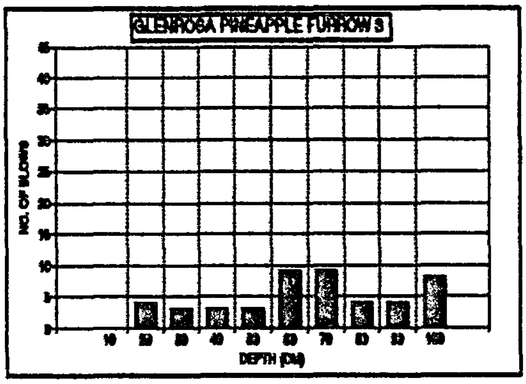

OAKLEAF PINEAPPLE RIDGE 8
NO. OF BLOWS
DEPTH (CM)

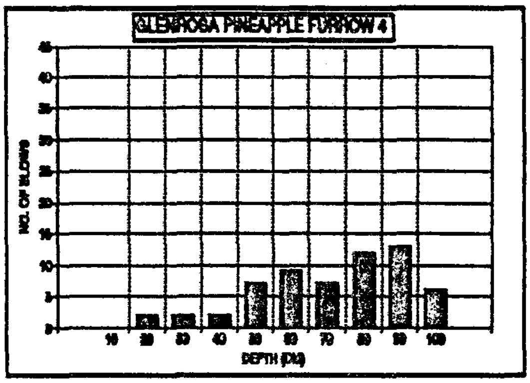

OAKLEAF PINEAPPLE RIDGE 9
NO. OF BLOWS
DEPTH (CM)

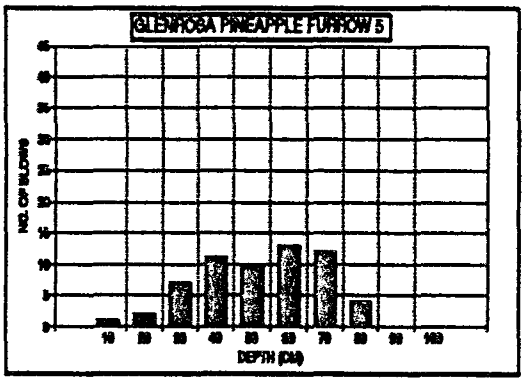

OAKLEAF PINEAPPLE RIDGE 10
NO. OF BLOWS
DEPTH (CM)

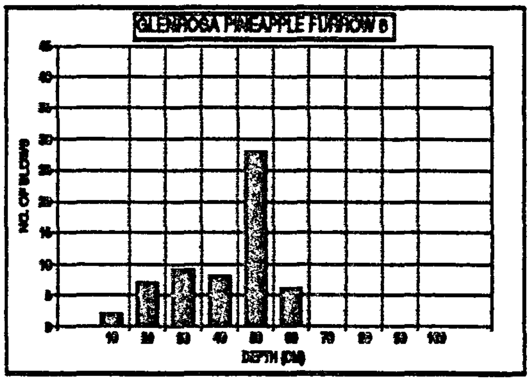

GLENROSA PINEAPPLE FURROW 1
NO. OF BLOWS
DEPTH (CM)

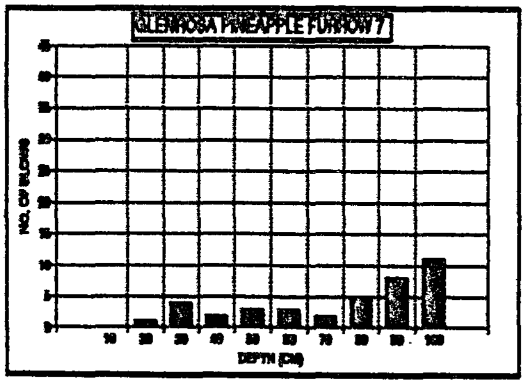

GLENROSA PINEAPPLE FURROW 2
NO. OF BLOWS
DEPTH (CM)

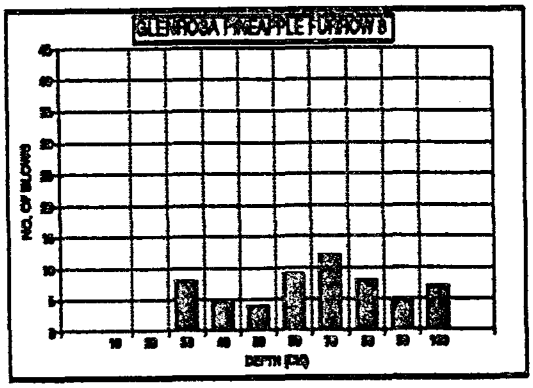

GLENROSA PINEAPPLE FURROW 3
NO. OF BLOWS
DEPTH (CM)

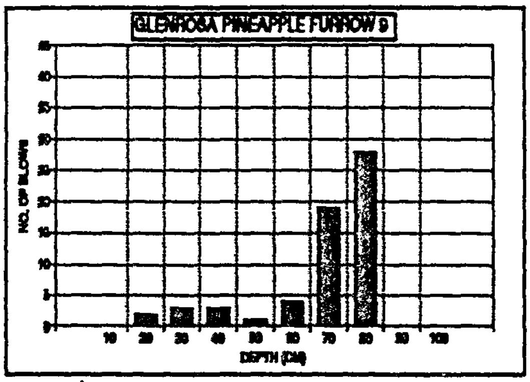

GLENROSA PINEAPPLE FURROW 4
NO. OF BLOWS
DEPTH (CM)

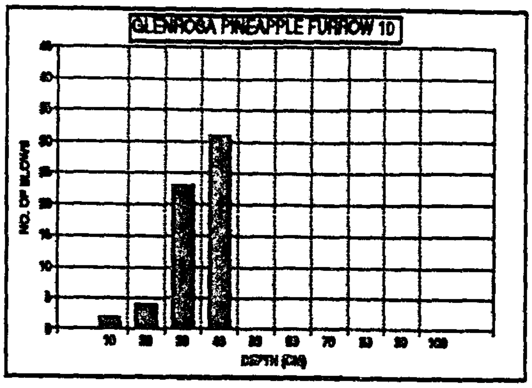

GLENROSA PINEAPPLE FURROW 5
NO. OF BLOWS
DEPTH (CM)

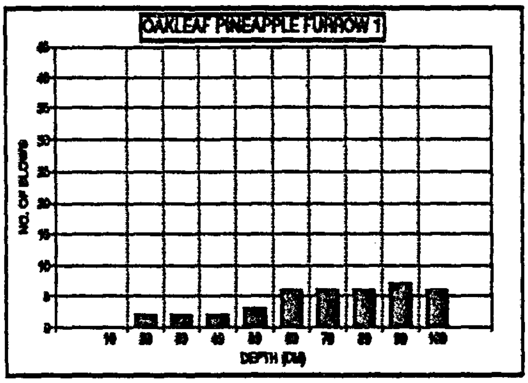

GLENROSA PINEAPPLE FURROW 6
NO. OF BLOWS
DEPTH (CM)

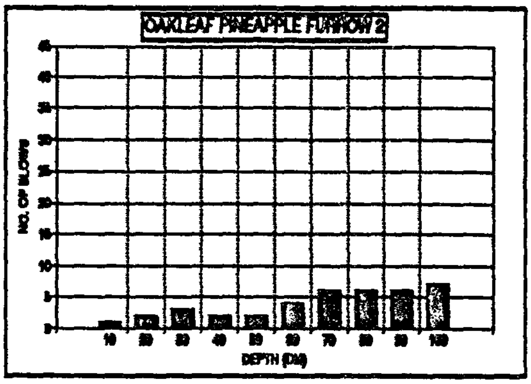

GLENROSA PINEAPPLE FURROW 7
NO. OF BLOWS
DEPTH (CM)

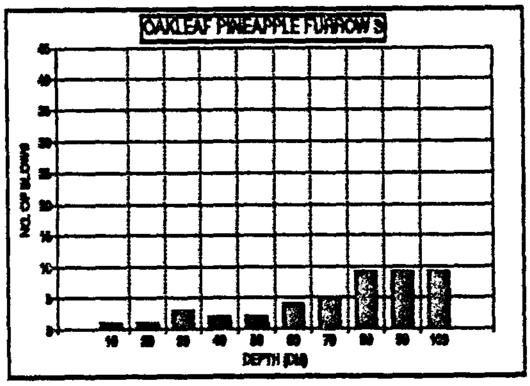

GLENROSA PINEAPPLE FURROW 8
NO. OF BLOWS
DEPTH (CM)

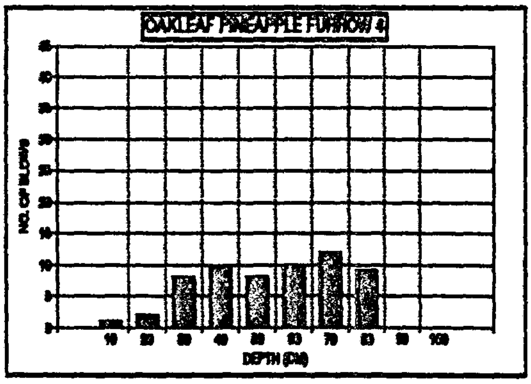

GLENROSA PINEAPPLE FURROW 9
NO. OF BLOWS
DEPTH (CM)

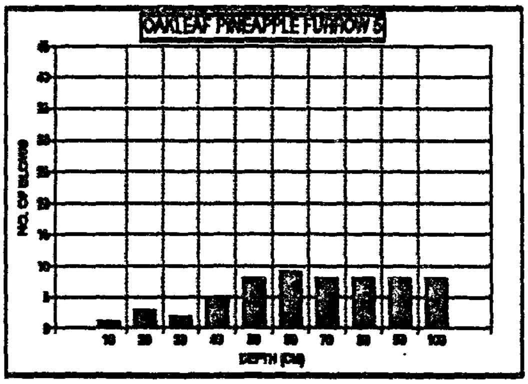

GLENROSA PINEAPPLE FURROW 10
NO. OF BLOWS
DEPTH (CM)

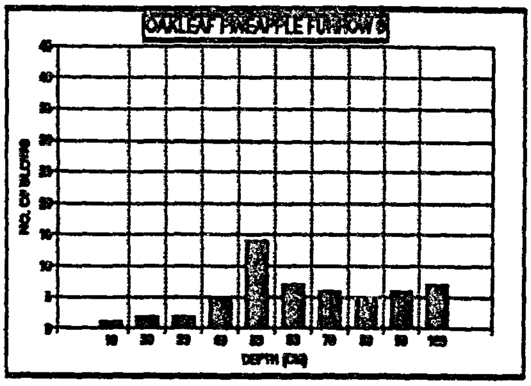

OAKLEAF PINEAPPLE FURROW 1
NO. OF BLOWS
DEPTH (CM)

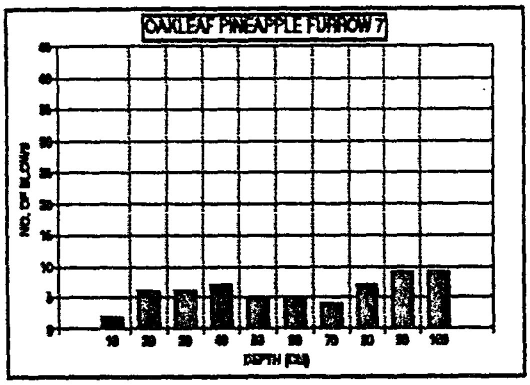

OAKLEAF PINEAPPLE FURROW 2
NO. OF BLOWS
DEPTH (CM)

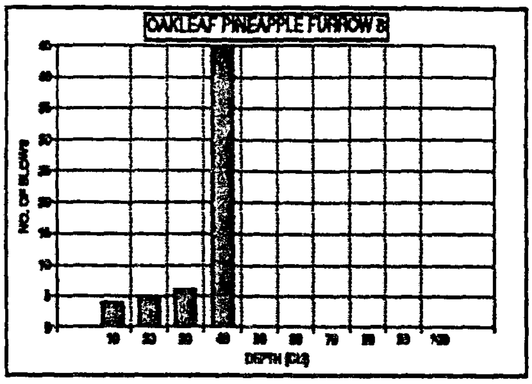

OAKLEAF PINEAPPLE FURROW 3
NO. OF BLOWS
DEPTH (CM)

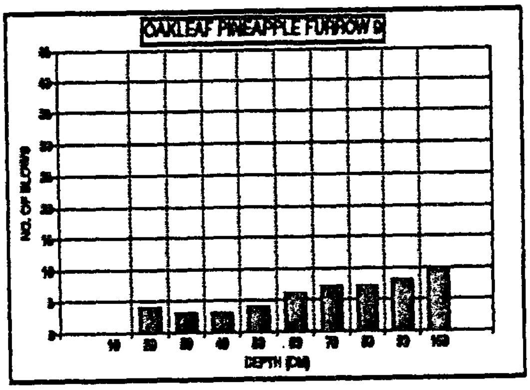

OAKLEAF PINEAPPLE FURROW 4
NO. OF BLOWS
DEPTH (CM)

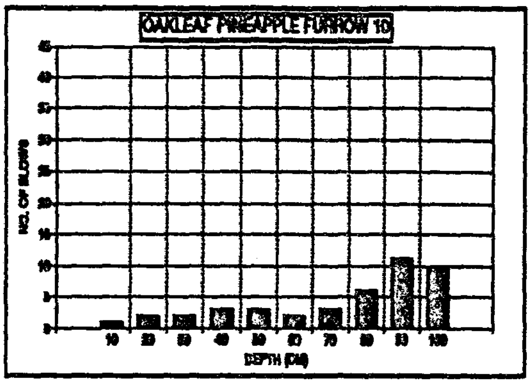

OAKLEAF PINEAPPLE FURROW 5
NO. OF BLOWS
DEPTH (CM)

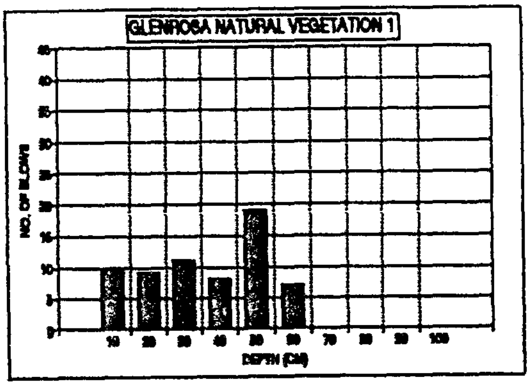

OAKLEAF PINEAPPLE FURROW 6
NO. OF BLOWS
DEPTH (CM)

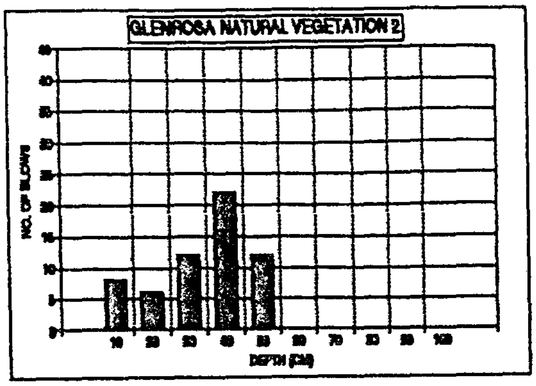

OAKLEAF PINEAPPLE FURROW 7
NO. OF BLOWS
DEPTH (CM)

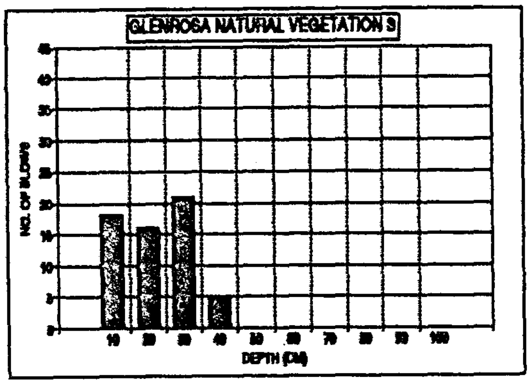

OAKLEAF PINEAPPLE FURROW 8
NO. OF BLOWS
DEPTH (CM)

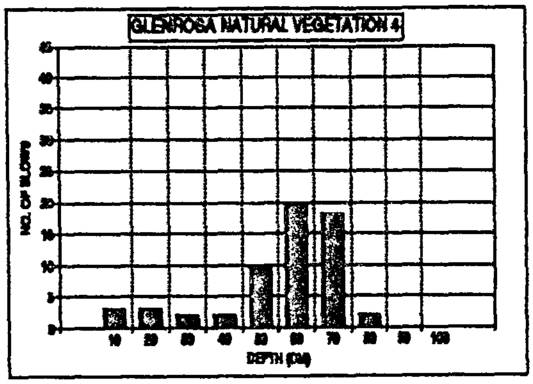

OAKLEAF PINEAPPLE FURROW 9
NO. OF BLOWS
DEPTH (CM)

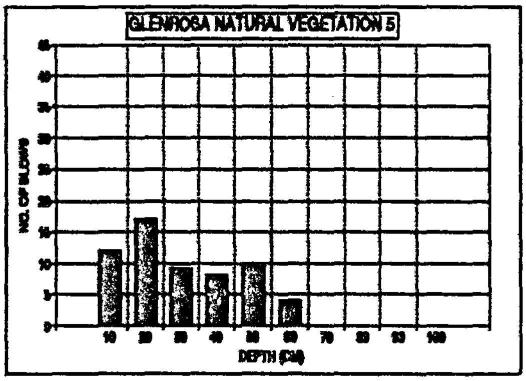

OAKLEAF PINEAPPLE FURROW 10
NO. OF BLOWS
DEPTH (CM)

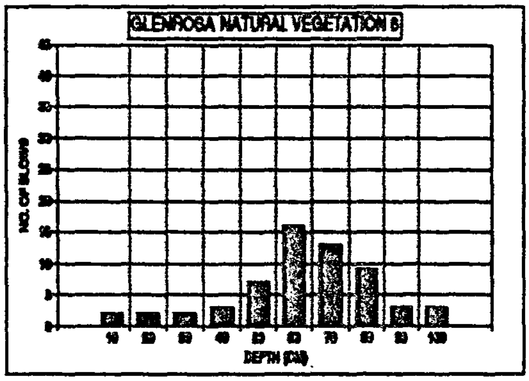

GLENROSA NATURAL VEGETATION 1
NO. OF BLOWS
DEPTH (CM)

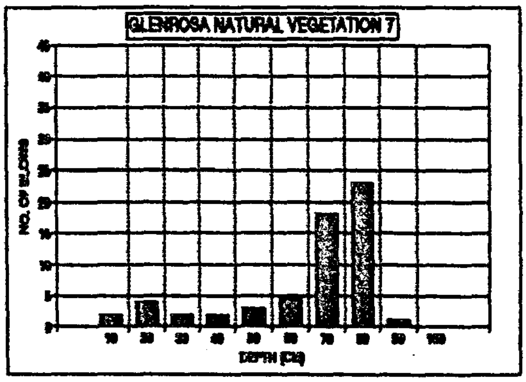

GLENROSA NATURAL VEGETATION 2
NO. OF BLOWS
DEPTH (CM)

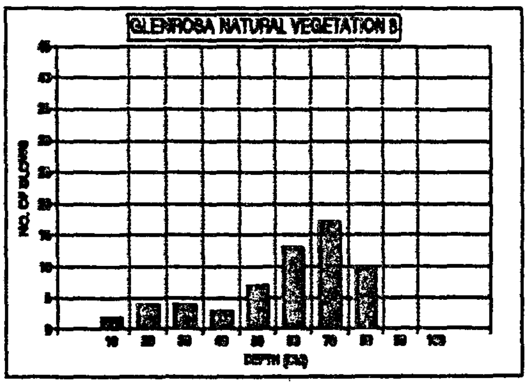

GLENROSA NATURAL VEGETATION 3
NO. OF BLOWS
DEPTH (CM)

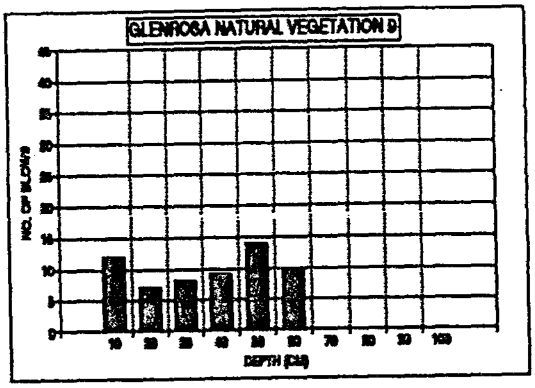

GLENROSA NATURAL VEGETATION 4
NO. OF BLOWS
DEPTH (CM)

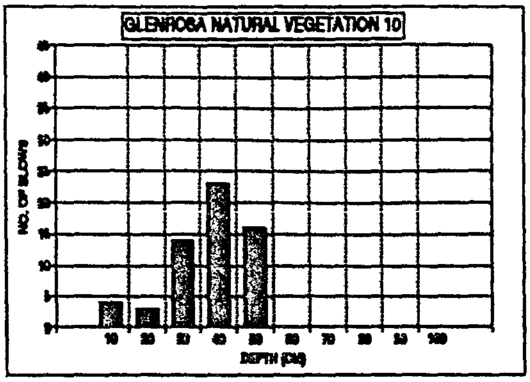

GLENROSA NATURAL VEGETATION 5
NO. OF BLOWS
DEPTH (CM)

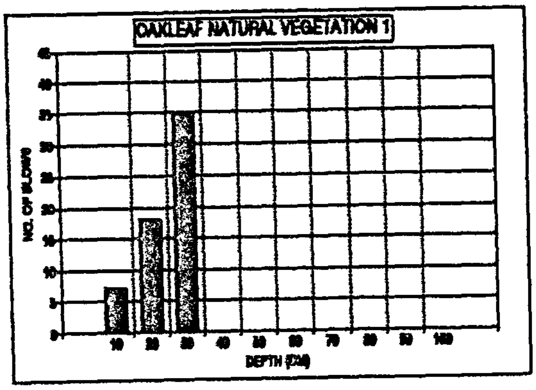

GLENROSA NATURAL VEGETATION 6
NO. OF BLOWS
DEPTH (CM)

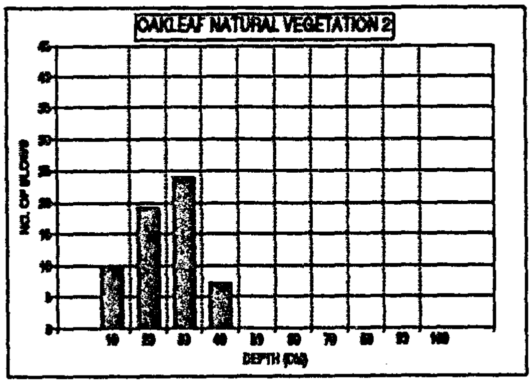

GLENROSA NATURAL VEGETATION 7
NO. OF BLOWS
DEPTH (CM)

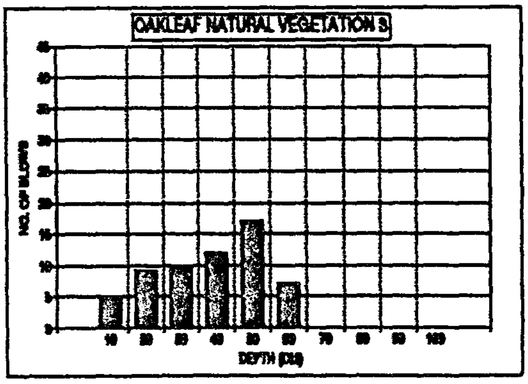

GLENROSA NATURAL VEGETATION 8
NO. OF BLOWS
DEPTH (CM)

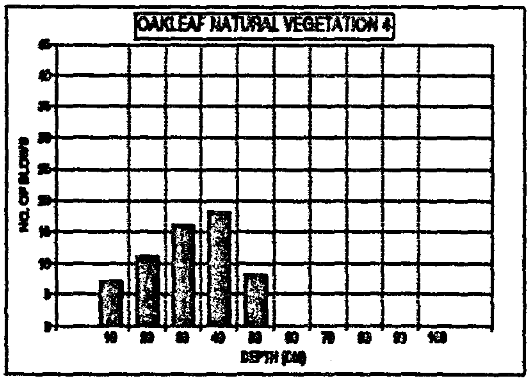

GLENROSA NATURAL VEGETATION 9
NO. OF BLOWS
DEPTH (CM)

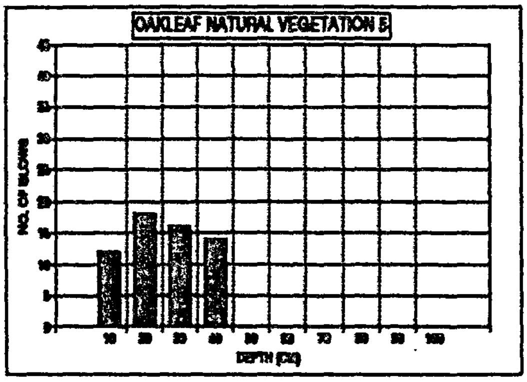

GLENROSA NATURAL VEGETATION 10
NO. OF BLOWS
DEPTH (CM)

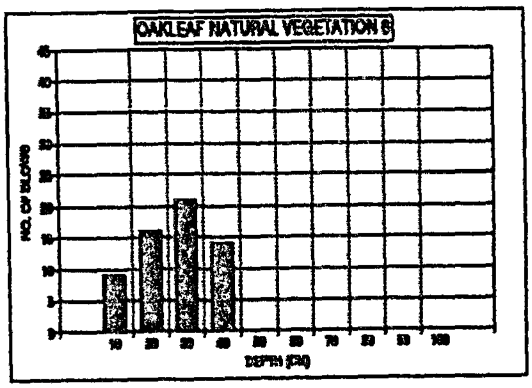

OAKLEAF NATURAL VEGETATION 1
NO. OF BLOWS
DEPTH (CM)

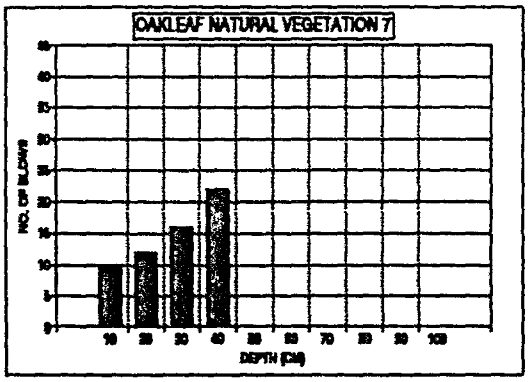

OAKLEAF NATURAL VEGETATION 2
NO. OF BLOWS
DEPTH (CM)

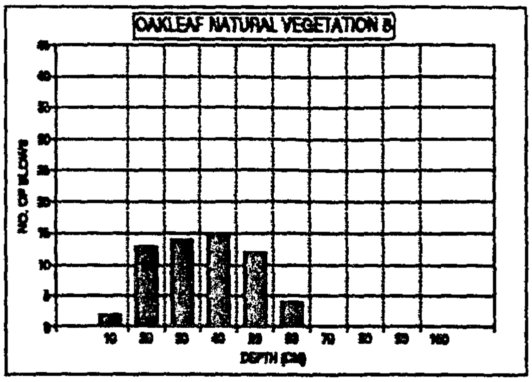

OAKLEAF NATURAL VEGETATION 3
NO. OF BLOWS
DEPTH (CM)

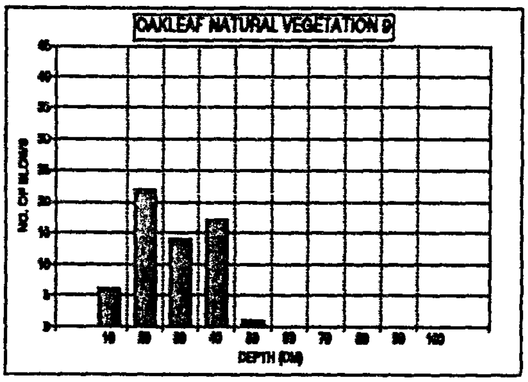

OAKLEAF NATURAL VEGETATION 4
NO. OF BLOWS
DEPTH (CM)

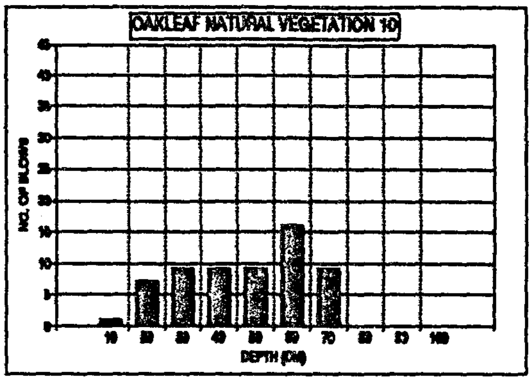

OAKLEAF NATURAL VEGETATION 5
NO. OF BLOWS
DEPTH (CM)


OAKLEAF NATURAL VEGETATION 6
NO. OF BLOWS
DEPTH (CM)


OAKLEAF NATURAL VEGETATION 7
NO. OF BLOWS
DEPTH (CM)


OAKLEAF NATURAL VEGETATION 8
NO. OF BLOWS
DEPTH (CM)


OAKLEAF NATURAL VEGETATION 9
NO. OF BLOWS
DEPTH (CM)


OAKLEAF NATURAL VEGETATION 10
NO. OF BLOWS
DEPTH (CM)