RELATIONSHIPS BETWEEN CLIMATIC INDICES AND SOIL PROPERTIES THAT REFLECT LEACHING AND WEATHERING IN THE NATAL MIDLANDS, AND THEIR USE IN THE ASSESSMENT OF AFFORESTATION POTENTIAL

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Submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy in the Department of Agronomy,
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December 1991

The exclusion of the monovalent cations from the calculation of ECEC enabled an even better fit of the data.

ECEC may be used to estimate MAER on well-drained sites, but, on the basis of a case study involving *Acacia mearnsii*, ECEC does not necessarily provide an estimation of the site index for timber, since tree growth is also dependent upon many other factors, the more so when rainfall is not limiting.

ECEC is recommended as a replacement for the S-value in the South African soil classification. For well-drained soils, ECEC is highly related to climatic indices, is less susceptible to seasonal change or change by land-use practices, and it is strongly covariant with many soil properties. Its use would bring about better alignment of the South African system with other soil classifications.

DECLARATION

I wish to certify that the work reported in this thesis is my own original and unaided work except where specific acknowledgement is made. Portions of this thesis have already been published as papers in the scientific literature in a form somewhat different to the form in which they are presented here. These papers are:

Donkin, M.J., 1989. The base status of soils for assessing afforestation potential: a preliminary appraisal. *Proc. 9th Site and Nutrition Working Group*, Sabie, May 1989, 38-45.

Donkin, M.J. and **Schulze, R.E.**, 1990. The determination of afforestation potential from soil property - climate relationships: I. The use of an agrohydrological model in the quantification of climate as a soil-forming factor. *S. Afr. J. Plant Soil*, 7(4): 230-235.

Donkin, M.J. and **Fey, M.V.**, 1991. Factor analysis of familiar properties of some Natal soils with potential for afforestation. *Geoderma* 48: 297-304.

This thesis has not been submitted for a degree in any other university.

Signed :

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List of Terms and Abbreviations

ACRU	-	An agrohydrological water-budgeting model developed by the Agricultural Catchments Research Unit, Department of Agricultural Engineering, University of Natal, Pietermaritzburg.
CCWR	-	Computing Centre for Water Research
CEC	-	Cation Exchange Capacity
Climofunction	-	A functional relationship between soil properties and climate (Jenny, 1941).
Climosequence	-	A set of soils that differ, one from another, in certain properties as a result of climate as a soil-forming factor (Jenny, 1941).
$cmol_c$	-	Centimoles of electrostatic charge
EC	-	Electrical conductivity
ECEC	-	Effective Cation Exchange Capacity (sum of the exchangeable bases and exchangeable acidity)
EGME	-	Ethylene glycol monoethyl ether
ICFR	-	Institute for Commercial Forestry Research, University of Natal, Pietermaritzburg.
MAER	-	Mean annual effective rainfall
MAD [ ]	-	Mean annual drainage [out of the B1 horizon, or the 50cm depth, as specified in square brackets]
MAP	-	Mean annual precipitation (refers to all forms of precipitation including hail and snow, and not only rainfall)
R_2O_3	-	The sesquioxides Al_2O_3 + Fe_2O_3
S-value	-	Sum of the exchangeable basic cations Ca^{2+}, Mg^{2+}, K^+, Na^+.
SSA	-	Specific surface area (m^2g^{-1})

List of Figures and Maps

List of Tables

ACKNOWLEDGEMENTS

I wish to thank the following people and organisations:

Prof. Martin Fey, Department of Agronomy, Pietermaritzburg, my supervisor, for his interest, encouragement, stimulating discussions and critical appraisals of the work.

The Institute for Commercial Forestry Research (ICFR), its patrons and its staff for support for this research project. In particular I wish to thank Prof. Peter Roberts for his backing, and those persons who helped me in the laboratory: Jill Pearce, Carol Cameron, Michael Chetty, Mary Galbraith, Sally Schwabe and Neill Cameron. The interest of Dave Garbutt and the polemical discussions of Colin Smith have been invaluable.

Prof. Roland Schulze, Department of Agricultural Engineering, for permission to use ACRU, an agrohydrological water-budgeting model developed by the Agricultural Catchments Research Unit, and for his valuable help in this regard. In addition, Dr. Mark Dent and staff of the Computing Centre for Water Research (CCWR), are thanked for the invaluable service that their organisation provides.

The staff of the Department of Agronomy are thanked for their help and for the occasional loan of equipment in the course of the research.

Prof. A.H.Wilson and Roy Seyambu of the department of Geology and Mineralogy are gratefully thanked for the XRF analyses of various soil samples.

I also wish to record my appreciation to the many farmers and organisations (in particular SAPPI, the Natal Parks Board, and the State Forestry organisations) that allowed me access to their land, and tolerated my questions, probings, excavations and provided assistance in the pursuit of this research; and to the many people that expressed their interest in my research.

And last but by no means least, I acknowledge and greatly appreciate the unconditional support and encouragement from Debbie, my wife.

"This is the vowel of earth
dreaming its root
in flowers and snow,

mutation of weathers
and seasons,
a windfall composing
the floor it rots into."

Seamus Heaney.
An extract from the poem *Kinship (IV)* in *North* (1975)

TABLE OF CONTENTS

INTRODUCTION

Afforestation in the summer rainfall regions of southern Africa has been subject for some time to expansion and is moving to an increasing extent into those areas that are considered to be climatically marginal, from the viewpoint of commercial forestry. For those involved in forestry planning and in the assessment of the afforestation potential of land, it is imperative that an estimate of the afforestation potential of any particular site considered for such purposes is reliably made. This is especially important given the high input costs of afforestation programmes and the long delay before a return on investment may be seen. Thus a correct or incorrect assessment will have major economic implications.

Among the many site factors that determine the overall afforestation potential of a site, water availability is regarded as the prime determinant of tree growth in the summer rainfall areas of southern Africa (Grey *et al.*, 1987, p.73). Most sites, however, considered for afforestation are likely to possess a paucity of climatic information. Extrapolation from the nearest weather station is apt to be risky, given the rapid changes that can occur in climate with distance (Jackson, 1974). It is therefore desirable that an alternative means of estimating indices of climate at the site, in particular the effective rainfall, is available.

Towards this end, for well-drained yellow-brown and red soils, a measure of the *base status* of the B1 horizon (the so-called S-value, sum of exchangeable bases, expressed per unit mass of clay) has been used by surveyors on the assumption that this presumed measure of the degree of leaching is directly related to the effective rainfall at the site. The S-value per unit mass of clay is taken from the definition of soil base status in the South African soil classification (MacVicar *et al.*, 1977; Soil Classification Working Group, 1991). Highly leached (dystrophic) soils, determined on the basis of this S-value expressed per unit mass of clay, are deemed to be desirable for afforestation as they are considered to occur in areas of high effective rainfall (Grey *et al.*, 1987, p.74). In consequence, a number of soil surveyors, forestry consultants, planners and managers have placed much store in the S-value, expressed per unit mass of clay, and have been influenced by it in determining the afforestation potential of areas, particularly those of marginal potential.

Nevertheless, it would be true to say that the use of the S-value per unit mass of clay as an estimator of a site's effective rainfall is not free of criticism (Donkin, 1989) and there have been many instances where the value of the S-value expressed per unit mass of clay for a site has been perceived as being at variance with the effective rainfall of that site. In the experience of the author, the soil property has on occasion been viewed by surveyors with suspicion or even discounted. It was observed that the S-value expressed per unit mass of clay makes no provision for differences in parent material or organic matter content, and that the inferences applied in its usage have not been subjected to the processes of validation.

A research project was initiated at the Institute for Commercial Forestry Research (ICFR) in 1987, to look at the validity of the S-value per unit mass of clay as a measure of a site's effective rainfall and to investigate the use of alternative soil properties for such a purpose. It was acknowledged at the time that such research would have implications for soil classification in this country, as well as in the general study of soil formation (pedogenesis). Bryant and Olson (1987) have observed that the questions asked in soil genesis research have often been dictated by the needs of soil survey.

It was realised that soils needed to be sampled at a number of sites at which important climatic indices were reliably known, and that the influences of the other factors of soil formation (such as organisms, parent material, topography and time) needed to be negligible, or if necessary, constant or stratified (in the case of parent material). Such an approach was soon seen to be applying the state factor model approach of Jenny (1941, 1980; and discussed more fully in Chapter 1) and this model has been commonly applied in such pedogenetic studies. Through the judicious selection of sites, a *climosequence* is essentially described, where soil properties are observed to vary predominantly as a function of climatic intensity. Functional, quantified relationships obtained between soil properties and indices of climate would result in *climofunctions*, using the terminology of Jenny (1941). Yaalon (1975) considers the solution of univariate functions (such as climofunctions) to be indispensable steps on the way to the solving of a more generalised model of soil genesis. Jacob and Nordt (1991) consider Jenny's state factor model of soil formation to constitute "... the original paradigm that allowed pedology to develop as a science". Such a study will therefore contribute to an overall understanding of soil genesis.

In addition to the fact that the Natal midlands has seen considerable afforestation expansion, MacVicar (1965a) has described the region as being one particularly suited to the study of the climatic factor in soil genesis and to an appraisal of the relative importance of the other soil forming factors. He indicates that climatic variations within the area are clearly reflected by soil differences. Van der Eyk (1965a) has calculated the moisture regimes of typical soils within climatic regions in Natal and van der Eyk *et al.* (1969, p.57) indicate that soil base status has a predictable zonal distribution that is patterned by climate, specifically effective rainfall. The Natal midlands (and especially the so-called Mistbelt) has been described by van der Merwe (1962, p.312) as a region where climate dominates the parent material as a soil forming factor "...due to the intensive weathering of the parent material caused by the high rainfall and high temperatures". Schönau and Fitzpatrick (1981) consider the soils of the forestry zones of the Transvaal and Natal to be closely related to the present-day climate of the area.

Work, however, relating soil properties to climatic indices in the region covered by this study is scanty, and in most cases is mentioned in passing. There has been no systematic attempt to functionally quantify any soil property - climate relationships observed in the Natal hinterland, or elsewhere in southern Africa. Where the topic has been approached, the objective has been chiefly to deal with aspects of soil classification, or to support pedogenetic theories of how soils in the region came to be derived (such as King, 1963; van der Merwe and Weber, 1963, 1965; MacVicar, 1965a, 1965b; van der Eyk, 1965a; van der Eyk *et al.*, 1969). These objectives are typical of almost all the work done on climosequences throughout the world.

Indeed, world-wide, most studies of this nature have been largely viewed as being academic, and a thorough scouring of the scientific literature reveals that even where quantification of similar relationships has taken place, there has been no *perceived practical use* for such functions and consequently there has not been much effort expended in treating such relationships in a scientific and statistical manner. This is despite the recognition that climate is often the pre-eminent soil forming factor and has resulted in the concept of the climatic zonation of soils and, indeed, much effort has been expended in the delineation of such zones (Jenny, 1941; Arkley, 1967; Sys, 1967). It is remarkable, given the frequent reference to "obvious" soil property - climate relationships, through the use of statements such as "the low content of exchangeable bases reflects the high rainfall of the area" (Gupta *et al.*, 1989) that a definitive study of this nature has not been undertaken before. Jacob and Nordt (1991) are perturbed at the lack of focus which often appears to characterise pedology as a science[1].

Furthermore, those relationships that have been described in the literature have been only concerned with the response of soil properties to the soil forming factors. With one exception (detailed below), no one has sought to examine the equations *in reverse*, so as to estimate the intensity of the soil forming factors from soil properties.

The only reference to work that has the estimation of relative effective indices of climate from soil properties as an objective, is that of Yaalon (1965, quoted in Yaalon, 1983, p.240), who found that for arid regions in Israel with inadequate climatic data, the effective rainfall can be estimated from the depth position of the maximum salt concentration in the soil.

The usual attitude or approach to relationships between soil properties and state factors has been summarized, perhaps unintentionally, in a statement made by Jenny *et al.* (1968) concerning the pedogenetic equation:

[1]Jacob and Nordt (1991) consider pedology to have lost sight of a coherent theoretical framework in which criteria for formulating and choosing research questions are provided, and consequently has not made consistent advances (see also section 1.1).

"For several predictor variables X_1, X_2, X_3, ... the linear multiple regression equation reads

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \ldots$$

... *we are not particularly interested in valid numerical predictions of Y from the X's* but rather in the contributions of the individual X's in explaining the variance of Y..." [my italics].

The principal objective of this research undertaking is therefore to establish a procedure for estimating, at least within the context of areas of interest to foresters, climatic indices such as the mean annual effective rainfall of a site, from soil properties at that site. For such an objective to be achieved, resulting in a usable, reliable and validated tool, the tactics employed and the concepts that need be covered may be outlined as follows:

i) Since the relationships between soil properties and climatic indices are concurrent with aspects of soil formation, a survey of the various conceptual theories and models of pedogenesis is required. In this regard, the adoption of an appropriate model will provide a framework for the research strategies which are to be employed. In addition, a survey of the literature will reveal the perceived relationships occurring between soil properties and climatic indices, and the extent to which soil classifications world-wide draw on such relationships. This investigation is presented in the form of a literature review in Chapter 1 of the thesis.

ii) A judicious selection of sites will involve the confirmation at each site of reliable long-term climatic data and the presence of soil forms and environmental considerations that are conducive to the study in question. To expedite this research, climatic information for each site needs to be in a data base and in a format amenable for direct input into computer models. Indeed, such work in the past may have been hampered by this requirement. At each site, the description and sampling of a representative soil profile will be required.

iii) Soil samples taken will undergo appropriate laboratory analyses. There is also some necessity to investigate what is meant by the terms *soil base status, degree of leaching* and *degree of weathering*, in the context of the study.

iv) For each site, indices of climate appropriate to soil formation will be calculated. It is also imperative that some consideration is made of the extent to which these indices represent the climate under which the soil formed.

v) Over the range of sites, various soil properties indicative of leaching and/or weathering will be related to pertinent climatic indices. The degree to which such relationships may be used to estimate indices of climate from soil properties will be gauged.

vi) By using a case study (of a commercial timber species), the extent to which tree growth (site index) relates to some of the more important soil property - climate relationships obtained previously, will be investigated.

While the principal aim of the research is to seek a means of estimating climatic indices from soil properties for the forestry regions of the Natal midlands, the research should also add to the growing body of literature pertaining to the genesis of soils in the humid, summer-rainfall regions of the world, and should also be of some general value to soil classification.

In short, this research entails the partial solution of a model of pedogenesis under the specific circumstances of a climosequence in the Natal midlands, and its application to the estimation of afforestation potential at sites within this region.

CHAPTER 1 A REVIEW OF CONCEPTUAL MODELS OF SOIL GENESIS, AND OF THE INFLUENCE OF CLIMATE ON SOILS AND SOIL CLASSIFICATION

Introduction

In ancient times, soil was commonly held to be an inert material that reflected only the composition of the underlying rock (Arnold, 1983). Soil is now considered to have been formed and to be in the process of formation as a result of the many environmental factors acting on the parent material. These processes of soil formation are of an on-going nature and are themselves subject to change. It is the subject of pedogenesis that is devoted to the consideration of the pedogenetic processes brought about by the soil forming environment, and the resultant profile characteristics (Duchaufour, 1977, p.3; Ugolini and Sletten, 1991). Buol *et al.* (1989) consider soil genesis to be the study of changes in the soil system with time. Towards this end, conceptual models are now considered an essential tool of modern pedological research (Dijkerman, 1974).

In the formulation of an approach to investigate the relationships between relevant soil properties and the soil forming climatic factors, the adoption of a conceptual framework, or model, is required. Not only must the soil properties and indices of climate themselves be considered, but also the means by which they interact.

Attention should also to be given to similar relationships noted in the literature in other parts of the world, and to the rôle that such relationships play in the major soil classification systems.

The objectives of this literature review are therefore:

(i) to consider the various conceptual models of pedogenesis. The adoption of a model would permit the development of a strategy whereby the relationships between soil properties and indices of climate may be pursued;

(ii) to review the general nature of the relationships between soil properties and indices of climate and climatic zones; and

(iii) to survey the use of soil properties presumed to reflect leaching and weathering in soil classifications.

1.1 Models of soil formation

The concept that soil is a function of a number of environmental factors dates back to the 1880s. Dokuchaev, in nineteenth century Russia, is the first to be credited with formulating a state factor equation (Jenny, 1961; Kohnke *et al.*, 1968), which considered soil to be a function of climate, the biosphere and the geological substrate. This concept has been subsequently expanded to include the factors of time and topography. Much of the discussion about these soil forming factors has been centred around the pioneering work of Hans Jenny and his co-workers since the 1920's, who actively pursued the development of quantitative expressions of the state factors, as tools in the understanding of pedogenesis. The state factors of soil formation that are generally recognized (being climate, parent material, topography, the biotic factor and time) are thought of as controls on processes that result in observable and measurable features. Temperature and precipitation were originally considered as separate state factors by Jenny (1936) but their interrelationship was recognised, and they were subsequently combined as the single state factor, climate (Jenny, 1941). It was recognized that each soil forming factor (apart from "time") has a geographical distribution and that the patterns arising from their interactions lead to different soils (Arnold, 1983). Jenny's model of the soil forming environment in terms of so-called state factors is the best known and most frequently used factorial model and has had a seminal influence in pedological research (Runge, 1973; Yaalon, 1975; Huggett, 1976). Consideration of soils using this model has been a great aid to understanding them (Greenland and Hayes, 1981, p.22), but in most instances the model has been applied in an explanatory manner, rather than in any strictly quantitative procedure. This model is discussed further in section 1.2.

State factors of soil formation, however, are external forces and as such are deterministic. They nevertheless have an indirect influence on the actual soil forming processes which may be regarded on a mechanistic level, and thus on the soil profile, which may be considered on a functional, or behavioral, level. Ugolini and Sletten (1991) present the following scheme:

state factor	←--→	soil forming processes	←--→	soil profile
deterministic		*mechanistic*		*functional*

The mechanistic view of soil formation is attractive and other alternative models of the soil-forming environment have been constructed from this viewpoint, such as those based around energy or thermodynamics (Runge, 1973), simulation modelling (Arnold, 1965; Kline, 1973), or combinations of all the above models (Huggett, 1975). Quantification of these models, however, is generally daunting, and they have largely remained conceptual in practice. It would appear from the literature that none of these alternative models have had the impact of Jenny's model and that there have been no serious attempts as yet to quantify these particular models (with the exception of a geomorphic model of Kirkby (1985), discussed later). Arnold (1965) has also pointed out that it is probable that no soil forming process is independent of associated processes or of the state factors. Those experimenters that have tried to directly measure some of the soil forming processes *in situ* have been relatively few, and have met with mixed results (Ranger *et al.*, 1991). Arnold (1983, p.12) is of the opinion that

> "..the exact combination of physiochemical and biological reactions that have actually transformed materials into soil horizons of a specific soil can never be known with certainty"

and that assumptions and generalizations will be implicit in any mechanistic description of soil formation.

Simonson (1959) has formulated a generalized process theory of soil genesis, being a process-response model; one that relies on (i) parent material accumulation; and (ii) horizon differentiation. In particular, Simonson postulates that horizon differentiation is concerned with additions, removals, transfers and transformations within the soil system, and that all processes occur in all soils concurrently, although to differing extents. Runge (1973), however, considers most of these processes to be in fact combinations of individual processes which need to be identified further. Arnold (1965) has extended the concepts of Simonson to form multiple working hypotheses of soil genesis in a pictorial manner. In an attempt to define functional boundaries for soil systems, Huggett (1975) devised a model of soil landscape systems as a model of soil genesis, but again, the model is largely conceptual and is pictorially depicted. While it is true that the process-response systems such as those of Simonson (1959), Arnold (1965) and Huggett (1975) have not as yet been adequately described, let alone quantified, Smeck *et al.* (1983) regards these sort of models as being the most meaningful models of soil formation. Huggett (1975) maintains, however, that it is not feasible to construct a macro-scale theory from extrapolations of processes operating on a micro-scale and that one should rather construct a model that focuses on the general structure of the whole soil system. Hillel (1991) considers that in an open system, soil as a whole entity is greater than the sum of its parts, as it includes their interactions.

Recent work by Kirkby (1985) has considerably advanced the mathematical description of soil formation - although predominantly from the viewpoint of soil profile development in a geomorphic context. Kirkby has, to differing extents, attempted to quantify the processes of percolation, solution equilibria, leaching, ionic diffusion, organic mixing, leaf fall, organic decomposition and mechanical denudation, in order to develop a model of hillslope development. Kirkby concedes that some simplification has been necessary, that there are processes occurring in the soil which have yet to be incorporated into the overall model, and that the model had not at that stage [1985] been compared with real soils. In the opinion of the author of this thesis, the model proposed by Kirkby is the first serious attempt to functionally model the soil forming processes for the whole soil system and holds great promise for the future. Unfortunately the model is largely concerned with the geomorphic evolution of hillslopes and is not as yet amenable to the investigation of soil property - climate relationships.

Runge's "energy" model (1973) is in fact a refinement of Jenny's state factor model (Yaalon, 1975), but is more process orientated, and gives priority to certain factors (Smeck *et al.*, 1983, p.70). It considers energy fluxes or vectors in the soil system, so that water available for leaching is an agent for gravitational energy, while organic matter production is dependent upon radiant energy. This model may be summarized as:

$$S = f(o,w,t)$$

where soil (S) is a function of organic matter accumulation (o), the amount of water available for leaching (w), and time (t). Although the model is consistent with the first and second laws of thermodynamics, it must be remembered that soil is an open system. Runge (1973) emphasizes the importance of water in pedogenesis by comparing soil profiles to chromatographic columns and described water flow through the soils to be the principal energy source for decreasing the soil's entropy. It is noted, however, that the model is independent of parent material. Furthermore, Yaalon (1975) does not consider leaching to be a suitable substitute for weathering and Huggett (1975) states that the model does not take into account geomorphic processes such as erosion and deposition. Given the complex and open nature of soil systems, and the doubtful attainment of equilibrium between many soil minerals and the surrounding solution, this model has been no easier to quantify or solve than Jenny's model (Huggett, 1976) and so far has only been used for the formulation of hypotheses of soil formation (Smeck *et al.*, 1983). Yaalon (1975) is of the opinion that this model does not constitute an advance on the basic tenets of the factorial model of Jenny.

In an attempt to merge the deterministic approach with the mechanistic approach, Kline (1973) has proposed a semi-deterministic mathematical simulation model using systems theory, but the model goes no further than to postulate a theoretical framework for the modelling of soil genesis (Sondheim *et al.*, 1981).

In a novel approach, Ugolini and Sletten (1991) have considered acidic ions to be a common denominator in both external state factors and in soil processes. They have proposed a model that contemplates the sources, the rôles and nature of proton donors (acids) in weathering and soil processes, by considering the additions, reactions and removals of such acidic ions in the soil system. The model attempts to meld state factors with soil processes on the notion that, on well-drained sites, soil processes are driven by proton donors and that the nature, strength and distribution of these proton donors is controlled by the external state factors. This model is largely concerned with the influence of the state factors on the biota of the ecosystem, and considers the biota, either directly or indirectly, to be one of the major sources of proton donors in soil. The writer sees a disadvantage to this model in that climate, for instance, is treated as a source of atmospheric inputs of protons and as a conditioner of the biota (and hence other proton donor sources), and that the rôle of rainfall purely as a leaching agent, is played down. In addition, the model does not actively take into account physical processes such as *lessivage*, nor has it been sufficiently quantified or verified as yet to enable it to be considered a rival alternative to other models of soil genesis.

Chesworth (1973) has suggested an even more simplified conceptual model and views all soils as being systems moving inexorably towards a state of equilibrium, being that of a residua system. He contends that in general the soil forming factors are not independent factors, and that time is the only truly independent and external factor, and that given sufficient time, the influences of all the other state factors will be obscured. He concedes, however, that before such a state is reached, it is the intensity of the other state factors that will determine the rate at which such a residual state is approached. Yaalon (1975) considers this model to be over-simplified, and that the validity of a trend line with time does not prove general disequilibrium or the absence of the steady-state in soils. Chesworth (1980) admits that the value of his artificial system is limited to describing the end point that a soil system might reach given sufficient time and consistent environmental conditions. Kronberg and Nesbitt (1981) have attempted to apply this concept by quantifying weathering in terms of elemental molar ratios. The net effect, however, is still that of weathering trends, with no quantitative relationships with the factors of soil formation.

It would appear that most of the models of soil genesis are conceptual in nature and that few are in the process of achieving mathematical solutions (a notable exception being the geomorphic model of soil profile evolution being formulated by Kirkby (1985) which is largely concerned with hillslope development), even for specific conditions, mainly due to the lack of adequate quantitative data regarding soil forming processes. In the opinion of Yaalon (1975) and Smeck *et al.* (1983), this has been the major constraint to model development. Yaalon (1975) goes further in saying that the theoretical basis of Jenny's model has in no way been successfully challenged by these other conceptual models of soil genesis.

A distinction should be made at this point between the largely conceptual models of pedogenesis (which have been discussed in this section) and the host of computational process models that simulate events such as: the leaching of, for example, pesticides or fertilizers through the soil profile; the soil water budget; or agricultural productivity. These models, such as LEACHM (Wagenet and Hutson, 1989), ACRU (Schulze, 1989), and SWIM (CSIRO, 1991) are not primarily concerned with the evolution of soil profiles and their characteristics, although they may be used as tools in the elucidation of such soil formation trends. For example, LEACHM is a one-dimensional finite-difference model designed to simulate the movement of water and solutes through both layered and non-layered soil profiles. As such, LEACHM does not take runoff into account (Petach *et al.*, 1991). ACRU is an agrohydrological modelling system which integrates the terrestrial hydrological system with agricultural applications. SWIM simulates, as its title suggests, water infiltration and movement in soils. All such process models have their advantages and disadvantages, are usually orientated towards specific sets of applications, and tend to emphasise the dynamic rather than the static. As pointed out by Wagenet (1990), while a quantitative description of leaching within the profile is being pursued with increasing vigour, the numerous models are all hampered by the problems associated with describing field-scale spatial variability, non-equilibrium systems, macropore flow of water and chemicals, kinetic-equilibrium sorption processes and the inherent spatial variation in soil hydraulic, biological and chemical processes.

In short, none of the process-orientated models or approaches is sufficiently advanced to provide an alternative in their own right to the empirical state-factor model described by Jenny (1941) *for the purposes of finding working relationships between soil properties and indices of climate.* Consequently, Jenny's model of soil formation is discussed in greater detail in section 1.2.

It has been stated that one of the objectives of science is the uncovering of truth (Philip, 1991). It must be pointed out that not one of the conceptual models discussed here is in itself the *truth*, but are themselves only means of simplifying the complex soil system, or of approximating the truth (Arnold, 1965). These models will only be of use in the formulating of theories if they lead to more rapid discovery of truth (Runge, 1973).

Jacob and Nordt (1991) suggest that the reason why pedology as a scientific discipline has not made consistent advances, is that in the terminology and discussions of Kuhn[2], it has not always taken place within a paradigm, being

> "a coherent theoretical framework that provides criteria for formulating and choosing research questions".

Jacob and Nordt (1991) consider Jenny's state factor model of soil formation to have been

> "...the original paradigm that allowed pedology to develop as a science"

but that, for reasons that are not readily apparent, research projects that sought to provide and work within a coherent model of soil and landscape evolution had been discontinued by the early 1970's.

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[2]**Kuhn, T.S.**, 1970. The structure of scientific revolutions. 2nd. ed., Univ. of Chicago Press, Chicago.

1.2 Use of the State Factor Model

From the previous discussions, it has been seen that the conceptual model of Jenny (1941) is, for pragmatic reasons, the most appropriate model to adopt. Using this model, a strategy may be formulated by which the relationships between soil properties and indices of climate may be investigated.

Jenny (1941, 1946, 1961) described soil, expressed in terms of its properties, as being a function of its environment, this being composed of climate c, organisms o, topography or relief r, parent material p, time t, and other unspecified factors such as the actions of man:

$$\text{Soil} = f(c,o,r,p,t,...) \qquad (1)$$

This equation has also been reduced (Jenny, 1961) to three state factors, being the initial state of the system (L_0), external flux potentials (P_x), and the age of the system (t):

$$\text{Soil} = f(L_0, P_x, t) \qquad (2)$$

These factors essentially define the soil in terms of variables which control the characteristics of the soil system, and not in terms of processes, causes or forces (Smeck *et al.*, 1983, p.69).

If it is assumed that a soil may be represented by its suite of soil properties and that the factors responsible for these properties act independently, then a change in any soil property may be expressed in terms of partial derivatives :

$$ds = \left(\frac{\delta s}{\delta cl}\right)_{o,r,p,t}^{dcl} + \left(\frac{\delta s}{\delta o}\right)_{cl,r,p,t}^{do} + \left(\frac{\delta s}{\delta r}\right)_{cl,o,p,t}^{dr} + \left(\frac{\delta s}{\delta p}\right)_{cl,o,r,t}^{dp} + \left(\frac{\delta s}{\delta t}\right)_{cl,o,r,p}^{dt} \qquad (3)$$

If one state factor is observed to vary while other state factors remain constant or vary ineffectively, then specific solutions of the equation may be sought. Stevens and Walker (1970) point out that it is the partial derivative of the soil property relative to these other factors which approximates zero, and not necessarily that the factors themselves are constant. Any soil property or set of soil properties may then be functionally related to any particular soil forming factor. For example, soil properties (s), according to Jenny (1946), are expressed in terms of climatic variables *c*, when *o, r, p* and *t* are constant:

$$s = f(c)_{o,r,p,t,...} \qquad (4)$$

A sequence of soils with climate as the only variable factor is designated a *climosequence* (Jenny, 1946). Similar sequences have been defined for variation in other state factors (Jenny, 1946; Yaalon, 1975): soil *toposequences* or soil *catenae*, where the major variable is topography; soil *chronosequences*, where the variable is time; and *lithosequences* where the variable is the soil parent material. The soil forming factors, however, are generally highly interrelated and consequently any consideration of the influence of one state factor, must of necessity take into account some consideration of all the other state factors.

In practice, the solution of the overall soil forming function (equation 1) is unlikely, given the large number of degrees of freedom (Yaalon, 1975), and its limited use is acknowledged by Jenny (1946). The resolution of the general equation into its univariate components, such as the one expressed in the equation $s = f(c)_{o,r,p,t,...}$, is of greater value. Nevertheless, the solution of the soil state function, for any particular set of univariate circumstances is not a straightforward task and is of restricted application. The reasons for this may be summarised as follows:

i) soil sequences where one of the factors varies while all the other factors remain essentially constant or vary ineffectually, are rare;

ii) some factors are discrete, non-overlapping units (Runge, 1973). The expression in numerical terms of these state factors, such as parent material is uncertain, although stratification and grouping techniques have been used (Jenny, 1941, 1946; Yaalon, 1975);

iii) soil property variability (both systematic and random) is notoriously difficult to account for (Wilding and Drees, 1983);

iv) the solution of the partial derivative equation assumes that the soil forming factors are independent (Chesworth, 1976a), but upon inspection this is not always the case. Time is considered to be the only truly independent factor (Stevens and Walker, 1970; Chesworth, 1973);

v) the model has an implied assumption (Barshad, 1964, p.60) that any particular soil is monogenetic, in that it has been formed under uniform circumstances from time zero, a condition that is not always met (Stevens and Walker, 1970) and in many environments may even be considered to be the exception rather than the rule;

vi) the model does not accommodate the incremental data required for determining the rates of change that are essential to the study of soil formation (Bryant and Olson, 1987); and

vii) the model fails to address the operation of soil forming factors (Bryant and Olson, 1987). Jenny himself has said that processes are not part of the state factor approach (Jenny *et al.*, 1968, discussion p.40).

Kline (1973) considers the equations for this model to be of incredible complexity, and in his opinion, probably completely intractable. Huggett (1975) considers the empirical equation approach of Jenny to be unworkable in practice when there are a vast number of processes that operate on a variety of time scales.

It is conceded that any quantitative relationship that is being described will be of a probabilistic nature, rather than being a perfect function, and indeed, there has been much debate as to whether the equation can be solved, or is even valid (Yaalon, 1975; Chesworth, 1976a, 1976b; Huggett, 1976; Yaalon, 1976; Smeck *et al.*, 1983). Furthermore, factorial models of this type are by nature empirical and reveal little about soil-system dynamics. Jenny's factors of soil formation, however, have had more impact on pedogenetic studies than any other soil model (Bryant and Olson, 1987) and remain the only viable means at present of elucidating relationships between soil properties and external forces. Jenny (1980) considers the model to be one which provides a means to separate landscapes into sections along vectors of state factors, which in turn provide avenues for understanding. Yaalon (1976) is of the opinion that the functional approach of Jenny, rather than the deterministic approach of Simonson and others, is more useful for the simple and pragmatic reason that the functional or statistical probability concept allows quantification even when the processes are too complicated for a deterministic treatment.

1.2.1 State factor climate

Climate as a soil forming factor, by implication, involves interactions between *inter alia* precipitation (e.g. rainfall, snow, hail), evaporation, temperature, humidity, rainfall seasonality, the quantity and intensity of rainfall, cloudiness and wind speed, with the soil. Climate is also known to indirectly influence the pedoclimate through the climatic control of vegetation, and the subsequent production of organic substances that influence soil formation (Duchaufour, 1977, p.96). The state factor climate involves both the local microclimate and the more global macroclimate. Buol *et al.* (1989, pp.151, 160) consider the macroclimate to be the interaction and impact of precipitation, temperature, radiant energy, and their diurnal and seasonal variations; and the microclimate to be dependent upon local attributes such as aspect, wind, soil colour and shading. Although highly important at a process level, the actual climate within the soil is regarded as a soil property and is considered to be highly related to the external climate (Buol *et al.*, 1989, p.163).

Jenny (1946) has, on occasion, resolved climate as a soil forming factor into moisture and temperature components, but most workers in this field have sought to combine the rainfall and temperature components, and have investigated the concept of effective rainfall, through the use of various indices of moisture effectiveness, as the individual effects of rainfall and temperature are hard to separate (Young, 1976, p.8). Yaalon (1975) states that more attention should be given to the seasonality and variability of rainfall distribution. This is discussed further in section 1.3.4.

It has been suggested that climatic extremes are more highly related to soil properties, than climatic means (Yaalon, 1983, p.243; Buol *et al.*, 1989, p.162). Such a situation would be expected to pertain to a greater extent in arid regions, where for instance, one high rainfall event may bring about greater leaching in a soil than the combined leaching events of the previous ten years. In any case, over the history of a soil's formation, a "mean of extreme climatic events" would have to be determined. Unfortunately, given the long time required for soil formation, and shortness of the climatic record for sites in most cases, the characterization of what constitutes a "mean of extreme climatic events" is difficult to contemplate.

The assumed constancy of climatic parameters has also been the subject of criticism (Yaalon, 1975). Any discussion of the soil forming climate must also consider the ability of comparatively recent climatic records (substantially less than a hundred years in most cases in southern Africa) to represent, not only long-term records, but the influence of the climatic fluctuations over the period of soil formation. Deductions, however, based upon evidence other than the climatic records recorded by man (such as incremental tree ring growth), for past climates or climatic changes, are generally too imprecise for quantitative use.

Usually, long-term climate deductions are often based upon short-term rainfall records (Dent *et al.*, 1988). In southern Africa, the last 40 000 years before present (B.P.) have been summarized by Meadows (1988). Tyson *et al.* (1975) have described regular cycles of relatively humid and arid phases with a length of approximately 10 or 11 years in the region. Longer-term cycles of even more marked fluctuations have also been observed (van Zinderen Bakker, 1976; Goudie, 1977, quoted in Meadows, 1988).

Nevertheless, Yaalon (1975) does not consider climatic fluctuation to invalidate the state factor approach, provided all sites selected have been subjected to the same fluctuations. It has been observed by Blosser and Jenny (1971) in a North American context that

> "... many soil properties are in accord with present day climate. Either climate has not changed significantly, in a pedological sense, for a long period of time; or the soil properties of past climatic regimes adjusted themselves to today's environment; or past climatic regimes are highly correlated with present-day climates."

It has been observed that in many cases, present soil forming process intensities are dominant over previous intensities. Dan (1983) describes the degree of leaching observed for Israeli soils as being especially related to the present climate for non-buried soils, but indicates that certain soil properties such as colour and texture may be related to previous climates. Jenny (1980, p.239) states:

> "Past climatic shifts are not disputed. Their severity is unknown. A higher rainfall accelerates, a lower one retards the leaching process without changing its character."

In southern Africa, on the evidence of clay mineral analyses of soils derived from basic and igneous rocks and other parent materials under different climatic conditions, van der Merwe and Weber (1965) deduce that soils in southern Africa have developed under specific climatic conditions and that no marked climatic changes have taken place during their evolution.

1.2.1.1 Climosequences and climofunctions

Referring to chronosequences, Jenny (cited by Stevens and Walker, 1970) has made the following statement:

> "We speak of chronofunctions when soil properties and ages are known quantitatively. If the ages are relative, we speak of chronosequences. There are various degrees of reliabilities of chronosequences."

This statement may be adapted to describe the concepts of the climofunction and the climosequence. The climosequence may then be defined as a sequence of soils that differ, one from another, in certain properties primarily as a result of climate as a soil forming factor. The assumption that soils in a climosequence are sequentially related along a climatic gradient, is not implied or necessary, although for most studies of climosequences this has been the case.

Often, climosequences studied have relied on the implied relationship of climatic indices to altitude in mountainous areas, with temperature decreasing and rainfall increasing with increasing altitude. Buol *et al.* (1989, p.161) consider such climosequences, while providing dramatic results, to be atypical, and suggest that climosequences are best observed over longer transects, with lower slope gradients. Yaalon (1975) considers that of the climofunctions that have been determined so far, few can be considered as sufficiently valid to allow generalisation.

1.2.2 Parent material

The state factor parent material is considered to affect soil formation through its inherent characteristics, such as texture, porosity, drainage, mineral composition and stratification (Ollier, 1984, p.162) and is considered to be of particular importance in determining the initial stages of soil development (Dan, 1983). With increasing intensity of the climatic factor, the relative influence of the parent material factor is expected to decrease (Juo, 1981; Dan, 1983), although even under extreme climatic conditions, such as those in the Amazon basin (rainfall > 3000mm per annum), the geochemical signatures of the original parent materials are reported to survive (Moura and Kroonenberg, 1988).

Not only do different parent materials have contrasting chemical make-ups, but they will also weather at dissimilar rates to each other. Base rich parent materials such as basalt and dolerite are considered to chemically weather more rapidly than the more acidic materials, rich in silica and quartz (Duchaufour, 1977, p.148). There are also some parent materials such as pure sand, ore bodies, or limestones which give rise to specific soils greatly dominated by the parent material, although these are considered to be 'extreme' cases by Ollier (1984, p.163).

The relative porosities of different parent materials will influence the capacity of leachates to leave soil systems (Dan, 1983). For example, sandstone has been shown to be a lot more porous than granite or dolerite (Trudgill, 1988, p.31). A confounding factor is of course the actual physical weathering of the respective parent materials. Granite, for instance, fractures into blocks, which greatly facilitates the translocation of soil water out of the soil system. In general, the overall effect of parent material in a comparison of soils is to separate, or stratify, the group of soils into subsets according to the parent material.

In practice, complications often arise in determining the actual parent material(s) of any particular soil. Barshad (1960) has emphasised the need for establishing parent material uniformity before measuring subsequent changes brought about by soil formation.

1.2.3 Organisms

Organisms, in particular vegetation, are regarded as state factors of soil formation that are dependent upon the ecosystem, varying concomitantly with soil properties (Yaalon, 1975). Jenny (1958, quoted by Yaalon, 1975) defines the biotic factor as the *potential* floristic list, and not necessarily the *actual* vegetation present. The biotic state factor is therefore difficult to identify and quantify, given the recent impact of man in many cases, and the biofunctions and biosequences obtained to date have been few.

It must be noted that the vegetation present at a site is actually a dependent variable or response of the ecosystem to the state factors on the right hand side of the state factor equation (1) in section 1.2, including the potential vegetation. Likewise the fauna of an ecosystem will correspond in a similar manner. The influence of man is usually dealt with separately (see section 1.2.6). Consideration of the vegetation factor for the purposes of this study is dealt with in section 2.2.3.

1.2.4 Topography

The state factor topography, or relief, is considered to only influence the redistribution of matter and energy without contributing anything new (Huggett, 1975). Jenny (1946) also noted that the state factor relief also includes certain hydrological features such as drainage. While some researchers consider the soil catena as a unit landscape system in that all soils within a catena are interlinked (Dan and Yaalon, 1964), most workers in the field prefer to consider topography as a soil forming factor which should be dealt with on a consistent basis. In general, soils on slightly undulating land have been preferred, as soils formed on unstable, steep slopes are generally more youthful due to erosion (Dan, 1983).

1.2.5 Time

Time *per se* is not a soil forming factor, but is the framework in which the other state factors may be considered to operate. In some senses it may be regarded as a multiplier of the other soil forming factors. In most of the studies of chronosequences, relatively estimated soil ages, rather than exact time scales are used (Dan, 1983), as the establishment of a reference point to which all soils can be related can be difficult. Soil age, particularly for mature soils is a difficult property to estimate, and assumes that soils are monogenetic. Most chronosequences studied have been limited to sites with soils than are relatively youthful (usually much less than 10 000 years old).

So-called *mature* soils, such as Oxisols and Ultisols (Soil Survey Staff, 1975), are considered to have developed over time scales of the orders of tens and hundreds of thousands of years or more (Bockheim, 1980) and represent the late Quaternary. Jenny (1941) considers mature soils to be those soils which may be considered to be in equilibrium with the environment. Marbut (1951) maintains that mature soils are those affected mainly by the climate and biotic factors and that they generally characterize a topography that is slightly undulating. Young (1976, p.53) considers *immature* soils to be those in which horizon differentiation has not had sufficient time to take place.

In an attempt to account for the development of a soil "thickness" and the effects of erosion and deposition, Buol *et al.* (1989, p.132) have extended the state factor time to one of *space-time*, a continuum in which all things exist. A soil is considered to have existed from its $time_{zero}$ (t_o) and $space_{zero}$ (e_o) to its $time_{present}$ and $space_{present}$.

For the purposes of this study, if we can assume that at all sites in a climosequence, time of soil formation is roughly similar (of the same order of magnitude), and that no significant erosion or deposition has taken place, then it is immaterial whether or not the soils present at these sites are in a true steady-state or equilibrium, as climate will be distinguishing the rate of pedogenesis (Duchaufour, 1977, p.148) and thus the position of soils along a weathering trend-line, provided that all the soils used are not immature (in age terms), but have not reached a stage of senility. While Chesworth (1973) indicates that given enough time, all soils attain the same residual state, he also concedes that it is the intensity of the other soil forming factors which dictate the rate at which such a residual state is approached. It is contended that the relative importance of differences in soil age will be diminished if all soils on the sites sampled are mature, displaying the characteristics of mature soils such as appreciable horizon differentiation (Young, 1976, p.263).

that were formed under previous climates. Harradine and Jenny (1958), however, and Jenny *et al.* (1968) present evidence that strongly correlates many soil properties to present day conditions. It is asserted for this study area (California), that there has either been little pedologically measurable change, or that soil features have readjusted themselves to present conditions. Blosser and Jenny (1971) also suggest that there may be high correlations between past climatic regimes and the present one. That soils may reflect the influences of past climates, different from the present one, is not disputed (Buol *et al.*, 1989, p.162), although their interpretation is subjective (Hall, 1983, p.131).

While much of our knowledge of soil genesis has been derived from studies in the Northern Hemisphere, Squires (1988) has indicated that landscapes in the Southern Hemisphere have a physiography and palaeohistory very different from the Northern Hemisphere, and that in particular, large portions of southern Africa and Australia are characterized by relative geological stability with the existence of old landscapes.

While obvious evidence of palaeosols, such as buried soils, would exclude such soils from a study of this nature, the possibility that some of the sites sampled possessed palaeosols *which had adapted to today's climate*, nevertheless exists. For example, red apedal soils are known to occur within arid regions of the Tugela valley and, morphologically, are considered to constitute possible evidence for past, more humid climates (van der Eyk *et al.*, 1969, p.52). Nevertheless, many of the characteristics of these soils, such as measures of soil base status, are aligned with the present day semi-arid climate. Despite the possibility of sampling such relic soils, none of the soils sampled had properties indicative of weathering and/or leaching that were considered to be substantially out of kilter with the present day climate (see Chapter 4). Ollier (1984, pp.135-136) suggests that the influence of a past climate should only be invoked when the present conditions are incapable of accounting for observable phenomena.

1.2.6 Anthropogenic influences

The influence of man on the soil ecosystem was originally incorporated within the organism state factor, as an impartial factor (Jenny, 1946). It is now recognized, however, that man has a substantial capacity to initiate and alter the state factors of soil formation in a relatively short time span, and this anthropogenic state factor differs from the other state factors in that the actions of man may often be goal-directed (Amundson and Jenny, 1991). Although limited essentially to case studies, Amundson and Jenny (1991) have considered in some detail the state factor of man, and have allocated variables associated with their genotypes, phenotypes and culture to the factor.

1.3 Relationships between soil properties and climate

1.3.1 The zonality concept

It has long been known that *typical* soils are associated with certain climates and that these soils are to a large extent assumed to be controlled by climate (Lelong and Souchier, 1982, p.94; Ollier, 1984, pp.164-165). This is expressed in the concept of zonal soils which originated in Russia in the nineteenth century, and still forms the backbone of the current Russian soil classification. While all the state factors of soil formation (except time) are considered to have some geographical expression (Arnold, 1983, p.11), Buol *et al.* (1989, p.150) comment that the climatic and soil gradients appear to be highly congruent on a global scale. Ollier (1976) states that climate also plays a major part in geomorphology and in the slope formation processes.

Soils associated with specific zonal climates have been identified by many researchers all over the world, for example: Arkley (1967, soils of the United States); Hurst (1967, soil groups in New Zealand); Young (1976, p.60, soils of the tropics); Chittleborough (1981, red-brown earths of Australia); Tavernier and Sys (1986, red soils of central

Africa); and Verma *et al.* (1987, hill soils of Himachal Pradesh, India).

Zonal soils are not to be thought of as mutually exclusive and a continuum of soils is to be observed in general. For instance, Perraud (1971, quoted in Duchaufour, 1977, p.411) showed that subclasses of soils in the Ivory Coast were arranged in latitudinal zones in which base saturation of the soil increased regularly from south to north as the rainfall decreased and the length of the dry season increased.

In South Africa, Fitzpatrick (1978) has related the degree of aluminium substitution in Fe oxides to climatic conditions, and found that goethite (α-FeOOH) is found under conditions of cool and temperate humid conditions, whereas haematite (α-Fe_2O_3)is found under warm tropical and subtropical conditions, lepidocrocite (γ-FeOOH) is found in non-calcareous soils of temperate climates, maghemite (γ-Fe_2O_3) in warm tropical and subtropical soils, and Iron (III) hydroxide of variable composition (e.g. $Fe_4(O_3H_2)_3$) in acid soils of cool and temperate climates.

While van der Merwe (1962, pp.339-344) has concluded that the concept of climate zonality does not hold for most of South Africa, given the varied geology and topography often encountered, he describes the Mistbelt as being one of the regions in which climatic zonality generally does hold. Van der Eyk *et al.* (1969, p.57) describe that for the Tugela valley region, a measure of base status (in this case the sum of exchangeable basic cations expressed per unit mass of soil) has:

> "a predictable zonal distribution which is patterned by climate, specifically by effective rainfall".

Orchard (in discussion, van der Eyk, 1965a) has questioned climate as the dominant soil forming factor in parts of Natal, in the light of experience obtained from the sugar-cane growing industry, where parent material has assumed a more important differentiating rôle than climate. He concedes, however, that in the cane belt [1965], the climate is relatively uniform and that the soil forming factor parent material may not be dominant over climate in other parts of Natal, such as the Natal midlands region of this study.

Stoch (1976, pp.106-107) also questions the notion of climatic zonality for South Africa as a whole, and states that:

> "It is not always possible to reconcile past climatic influences with soil genesis, which is, to a large extent, unknown for the identified profile and the current situation".

Stoch further quotes Gous (1976) as having reported the occurrence of eutrophic and dystrophic soils of the same soil form in a single locality, and van der Walt (1976) as having referred to a correlation of parent material and the degree of leaching (presumably as defined in 1976, and for South Africa as a whole). Stoch concludes that experience gained in Natal (referring to the Tugela basin study, van der Eyk *et al.*, 1969), with its relatively high rainfall, cannot be directly applied elsewhere in the country and that a distinction based on leaching is artificial and not "natural".

1.3.2 Weathering/leaching sequences

As climatic intensity increases across a climosequence, the increase in the intensity of weathering is reflected in the formation of a sequence of clay minerals. Such clay mineral sequences are well documented in textbooks (for example: Garrels and Christ, 1965; Duchaufour, 1977; Pedro, 1982; Buol *et al.*, 1989). For well-drained soils, these processes are accompanied and aided by the leaching processes.

Arkley (1967) made a detailed classification of well-drained North American soils, relating climatically controlled drainage and the processes of transport. Duchaufour (1977, p.98) has summarized the sequence, with increasing intensity of climate:

i) Arid climate with practically no drainage (potential evapotranspiration always greater than precipitation): no material, even the most mobile ion (Na^+), is removed from the profile, leading to salsodic soils.

ii) Weak annual drainage: removal of Na^+ ions and incomplete decarbonation of the upper horizons.

iii) Climatically controlled drainage less than about 150mm per annum: complete decarbonation of the surface horizons, accumulation of $CaCO_3$ within calcic horizons - there is no clay migration or transport of sesquioxides.

iv) Climatically controlled drainage between 150 and 400mm per annum: moderate downward translocation of clays accompanied by a weak to moderate acidification of the absorbent complex; no calcic horizon is formed, the Ca^{2+} ions being removed from the profile.

v) Climatically controlled drainage greater than 400mm per annum: considerable downward movement of clays accompanied in cold climatic zones by a strong acidification with cheluviation; migration of Al^{3+} and Fe^{2+} as complexes.

In southern Africa, King (1963) states that calcrete deposits are not formed in areas with a mean annual rainfall of more than 500mm. Young (1976, p.71) suggests that a major pedogenetic boundary is marked by the division between pedalfers (all those mature soils of the humid tropics that have free or slightly impeded drainage (Young, 1976, p.127)) and pedocals (soils with free calcium carbonate (Marbut, 1951)) in the lowland tropics on freely-drained sites, at a MAP of 600mm. Gansen (1972, quoted in Duchaufour, 1977, pp.126-127) describes a typical succession of soils in humid climates, where soil differentiation is mainly the result of climatically controlled weathering. With increasing intensity of climate, there is a greater mobilization of iron and aluminium while the loss of silica in drainage water increases. At the same time the acidity of the profile increases and clay neoformation takes place, according to the sequence:

2:1 clay → 1:1 clay (kaolinite) → 1:1 clay + gibbsite

This can be equated to the sequence:

fersiallitisation → ferrugination → ferrallitisation as used in the French classification system (Duchaufour, 1977, pp.148, 162) and has been observed in central Africa (Tavernier and Sys, 1986). This succession is clearly seen where the parent material is the same, and precipitation increases and the importance of the dry season decreases.

Ferrallitic soils are reported to occur in the humid tropics in areas with rainfall higher than 1000 - 1200mm per annum and fersiallitic soils to be formed under present day tropical conditions with a rainfall lower than 1000 - 1200mm per annum (Sys, 1967). Sys (1976) discriminates between the two groups of soils on the basis of their base saturation, and their silica:alumina ratios. MacVicar (1965a) considers ferrallitic soils in southern Africa to occur under a rainfall regime varying between about 860mm and 1170mm per annum. Sys (1967), however, considers the findings of MacVicar (1965a) to reflect soils in a state of disequilibrium with a present more-arid climate, than that under which they were presumed to have been formed. It may be shown, however, that although the soils may have been initially formed under a more humid climate than the current one, many of the soil properties are directly related to current climatic indices (see Chapter 4).

Van der Merwe and Weber (1963, 1965) have studied the clay mineralogy of soils formed under a range of climatic conditions on different parent materials in South Africa. The clay minerals of soils formed from granite in the summer-rainfall region range from illite and traces of kaolinite with illite-montmorillonoid mixed-layer mineral in the decomposing rock under semi-desert conditions, to kaolinite, gibbsite, goethite and hemaetite at a MAP of 900mm and higher (van der Merwe and Weber, 1963). The changeover from the dominance of illite to kaolinite is reported by them to take place under a MAP of 500mm.

Van der Merwe and Weber (1965) have also investigated a similar sequence of clay minerals formed from dolerite under different climatic conditions. Under low summer rainfall (MAP $<$ 350mm), an illite-montmorillonoid mixed-layer is the dominant clay mineral with the presence of montmorillonite. At above a MAP of 800mm, chemical weathering and leaching become more intensive and kaolinite is the dominant clay mineral, and may be accompanied by gibbsite, goethite and hemaetite.

1.3.3 Climosequences in the literature

Climate, as a state factor of soil formation, has been observed to have major effects on many soil properties, including soil acidity, base saturation, soil organic matter, carbonate content and soluble salts (Young, 1976, p.59). Quantitative, univariate climosequences described in the literature have been relatively few and of varying detail. Many of the specific relationships examined have been summarized by Yaalon (1975) and Jenny (1980). There are of course numerous references in passing to the relationships between soil properties and indices of climate (usually mean annual precipitation and/or temperature), but these are not considered here in any detail. The following list is a selection of soil properties by means of which climosequences have been characterized:

Soil property	Researchers
Depth to calcium carbonate layer	Jenny and Leonard, 1934; Arkley, 1963; Honeycutt *et al.*, 1990a.
Calcium carbonate formation	Marion, 1989.
Depth to maximum salt concentration	Yaalon, 1983, p.240.
Clay mineralogy, free Fe_2O_3, Al_2O_3	Tanada, 1951; Simonett, 1960; Singer, 1966.
CEC of clay fraction	Singer, 1966.
Base saturation	Kohnke *et al.*, 1968; Ruhe, 1984b.
Acid saturation	Jenny, 1980, p.323.
pH	Prescott, 1931; Kohnke *et al.*, 1968; Jenny, 1980, p.322.
Exchangeable acidity	Jenny and Leonard, 1934; Jenny, 1980, p.322.
Desilication (SiO_2 loss)	Hay and Jones, in Birkeland, 1974.
Molecular ratios (eg. SiO_2:Al_2O_3)	Crowther, 1931; Tanada, 1951; Simonett, 1960.

Soil property cont.	Researchers
Clay content	Jenny and Leonard, 1934; Jenny, 1936; Harradine and Jenny, 1958.
Depth to maximum clay	Honeycutt *et al.*, 1990a.
Soil morphology	Coventry and Williams, 1984.
Nitrogen content	Jenny and Leonard, 1934; Harradine and Jenny, 1958; Jenny *et al.*, 1968; Kohnke *et al.*, 1968; Honeycutt *et al.*, 1990b; Spain, 1990.
Carbon content	Kohnke *et al.*, 1968; Honeycutt *et al.*, 1990b.
Phosphorus content	Honeycutt *et al.*, 1990b; Spain 1990.
Carbon to nitrogen ratio	Jenny, 1980, p.313.

Very few of these climosequences have been mathematically quantified, most having been presented graphically, and thus there is little indication of their correlation or degree of fit, or standard errors of estimation.

1.3.4 Modelling of climate

Mean annual precipitation (usually implying mean annual rainfall) is often used as an index of the effectiveness of available moisture. This parameter is the most commonly available climatic information available at any particular site and in many cases it constitutes the only available climatic information. For this reason much of the early research into quantifying the soil-climate relationship, while acknowledging its inadequacies in any accurate description, centred around the use of this parameter. At best it may be considered a gross climatic property of an area, as it does not take into account the nature and seasonal distribution of such rainfall, its variability from year to year and takes no account of other influences on moisture effectiveness such as temperature and evaporation. It nevertheless gives satisfactory correlations with many soil properties within regions characterized by rainfall of uniformly seasonal distribution patterns (Jenny, 1941).

While the data base for mean annual temperature is not as wide as that for mean annual precipitation, it has nevertheless been frequently used in soil property-climate studies because the fluctuations in annual temperature are not as wide as those for annual precipitation. Most climosequence studies, however, have preferred to treat temperature as a conditioner of effective rainfall, through its influence on evaporation.

1.3.4.1 A review of climate models

In measuring moisture effectiveness, numerous attempts have been made to improve on mean annual precipitation. Many of these are summarized and listed by Jenny (1941; 1980), Verheye (1982), Fanning and Fanning (1989), and Yair and Berkowicz (1989). The concept of climatic humidity, moisture effectiveness, or effective rainfall, in relation to soil science dates back to the early part of this century. Some of the broad approaches that have been attempted to improve on a quantitative description of soil moisture effectiveness are reported as follows:

1. The earliest empirical attempts were those of Transeau (1905), Lang (1920) and Meyer (1926). Transeau constructed a precipitation-evaporation ratio map of the Eastern United States, setting boundaries between arid and humid climates at the lines where precipitation equalled evaporation. It was noted at the time, however, that this ratio was difficult to determine experimentally. As a result Lang (1920) proposed the empirical precipitation-temperature ratio (the *Regenfaktor*), being mean annual precipitation (mm) divided by the mean annual temperature (°C). This index is reported to have some correlation with the distribution of soils (Buol *et al.*, 1989, p.154). The *Regenfaktor* has been modified (de Martonne, 1926, quoted in Jenny, 1941; Holdridge, 1947, quoted in Kohnke *et al.*, 1968) to account for mean annual temperatures less than zero°C, and thus negative ratios. Holdridge makes use of an "average annual biotemperature" by setting all mean daily temperatures less than zero to zero, and then takes an average for the year. The assumption is that at any temperature less than zero, all activities in the soil are essentially at a standstill irrespective of the extent

to which the temperature is less than zero.

2. Meyer (1926) suggested an alternative to this approach, the N-S (*Niederschlag Saatigungs*) quotient, being precipitation (mm) divided by the absolute saturation deficit of air (mm Hg). It has been used by Jenny (1941) to compare soil types found in the United States and Europe. Similar indices of climatic humidity were developed by Prescott (1949) and Voloboyev (1956)[3]. Voloboyev has used an annual precipitation (P) to evaporation (E) ratio to determine what are termed *hydroranges* and has related these to zonal soil groups.

The use of these empirical indices of climatic humidity has been largely restricted to the classification of broad soil groups, with some success (Hurst, 1967). Little work has been attempted in quantifying the relationship between specific soil properties and indices of climatic humidity, apart from the investigations of Kohnke *et al.* (1968).

The above indices of climate, however, are based upon annual means and do not take into account the nature and temporal distribution of the various parameters. The moisture regime of a soil is best considered in terms of the soil water balance, with the accommodation of rainfall distribution, temperature and potential evapotranspiration. Sys (1967) says that many of the empirical climatic indices described previously have not adequately defined the tropical soil zone.

3. Thornthwaite (1931, 1948) attempted to refine the concept of climatic humidity further by proposing a moisture classification based upon a summation of monthly moisture values which would account to some extent for seasonal rainfall distributions. Thornthwaite's Precipitation Effectiveness (or P-E Index) is nevertheless still empirical. Jenny (1941) says that this index corresponds better with the distribution of climatic soil types in the Great Plains area in the United States than those according to Lang (1920) and de Martonne (1926), but

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[3]**Voloboyev, V.R.**, 1956. Climatic classification of soils. *VIth Intern. Congr. Soil Sci.*, vol.V, Paris. Discussed by Sys, 1967.

does not present details. Several means of estimating potential evapotranspiration were devised, mainly based on temperature and latitude and have been modified and adapted by Penman (1948), Linacre (1977) and others. Ross (1989, p.75) describes the index of Thornthwaite as being the simplest for characterizing general profile development. P-E values of 128 and above are associated with tropical rainforests, and values less than 16 are associated with arid desert conditions. Ross (1989) considers this index as one of *moisture effectiveness*, with high values representing a net downward movement of drainage water and predominant leaching.

While all these indices of climatic humidity are an improvement upon the gross characteristics of mean annual precipitation and mean annual temperature, they have a number of drawbacks. Firstly they are more difficult to determine and they generally suffer from their hyperbolic nature in that whenever the denominator is small, the ratio becomes excessively large (Jenny, 1941) and they do not take into account site characteristics such as runoff. These empirical indices can be related to soil patterns and distributions, but they cannot be directly related to soil forming processes (Arkley, 1967). Jenny (1941) also points out that climatic records usually deal with the macroclimate of an area, but that many sites within such an area are characterized by a distinct microclimate that may be considerably different.

4. Measures of the amount of moisture that actually moves through the soil are usually referred to as leaching indices. While actual drainage from soil can be measured with lysimeters and then related to climatic conditions (Crowther, 1931), there have been too few comparable sites to permit accurate relationships to be derived. Using a leaching factor of Crowther's from Rothamsted (England), Hurst (1967) did not achieve satisfactory results in relating soil groups to water surplus for soils in New Zealand. Arkley (1963, 1967) formulated an index, the *leaching effectiveness of the climate* (*Li*), being defined as the sum of the excess of precipitation (P) over potential evapotranspiration (PET) during those months (or weeks) in which P is greater than PET. Arkley assumed that there was no runoff, and developed a set of curves describing the

water movement in a soil as a function of depth. This index, *Li*, has been successfully used to represent those climatic factors most closely related to the kind of zonal soils normally found under each climate in North America (Arkley, 1967).

The next logical step has been to model the soil water budget over smaller time intervals. The advent of high-speed digital computers has made possible, both practically and economically, extensive mathematical manipulations that would have been overwhelming in the past. A host of similar models have been developed and models simulating the soil moisture budget on a daily basis (or with even shorter time intervals) may now be routinely run. In general, one of the major constraints in the use of such models is the availability and capture of climatic inputs for such models in a format amenable to input into the models. It is important that the modelling of climate as a soil forming factor should take into account the porosity and water-holding capacity of the soil, as several inconsistencies in climosequences have been attributed to the variation in water-holding capacities of the soils considered (Dan and Singer, 1973). These parameters have been included in the algorithms of several models. The surface characteristics of soils are also important in the determination of moisture effectiveness, particularly in the very arid regions (Yair and Berkowicz, 1989).

1.4 Indices of leaching and weathering in soil classification

The purposes for developing a classification are (i) to create a system for organising knowledge; (ii) to deal with concepts; and (iii) to transmit knowledge[4]. According to MacVicar (1969), a soil classification is designed to accommodate the apparent soil individuals in the most satisfactory manner so as to allow the compilation of legible and meaningful soil maps, and to accommodate soil which has not been observed, but whose occurrence in nature can be predicted on the basis of observed property ranges

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[4]**Mill, J.S.**, 1925. A system of logic. 8th ed. Longmans, London. Quoted by Buol *et al.*, 1989, pp.18-20, 197-199.

and the *factors which govern soil formation*. In other words, soil classifications should also have some basis in pedogenesis and in the processes of soil formation.

Soil classification systems of the early part of this century were strongly influenced by the concept of climatic zonality and while regarding leaching as a function of climate, used environmental factors rather than soil properties (other than soil colour) for defining soil classes. Greater emphasis, however, came to be placed on soil properties that could be observed in the field or measured in the laboratory (Soil Survey Staff, 1975). In particular, base saturation and the accumulation of carbonates were used in the differentiation of soil moisture regimes and the associated degree of leaching in many classification systems. Limits of relevant soil properties, such as base saturation, were set by empirical correlation with observed sets of soils (Buol *et al.*, 1989, p.78), using the standard analytical approaches of the time.

Soil classifications have been strongly influenced by the historical conditions and purposes under which they have been developed and many have a strong nationalistic bias. There are some classifications, however, which have attempted to encompass a more global flavour, such as the classifications of the FAO/UNESCO (1974, 1988) and Soil Taxonomy (Soil Survey Staff, 1975).

Implicit in many classifications is that the criteria used to distinguish soils are those that (i) impart a large knowledge content; (ii) are linked to pedogenesis and land use; and (iii) may be used in the transfer of technology. Properties that have a large number of associated properties or that are highly covariant with other properties are used in order to minimise the criteria necessary to characterize and classify a soil (Buol *et al.*, 1989, p.20). A soil property thus should be able to serve a number of functions. Those properties that can be easily changed by land-use practices should be avoided (MacVicar, 1969).

A brief survey will now be presented of soil properties indicative of leaching and/or weathering as used in some soil classification systems.

1.4.1 Soil Taxonomy

Soil Taxonomy (Soil Survey Staff, 1975) is the official soil classification of the United States. It was developed by the U.S. Department of Agriculture and is widely used elsewhere (Ollier, 1984, p.160). Duchaufour (1977, p.172) considers the principal merit of Soil Taxonomy to be that most of the criteria used to differentiate soils are quantitative. It uses soil genesis themes and assumptions as a guide to the selection of soil properties as criteria (Buol *et al.*, 1989, p.4). A taxonomic update to this system "Keys to Soil Taxonomy" (Soil Survey Staff, 1987; discussed by van Wambeke, 1989) has also been published. Soil Taxonomy, however, has been criticized for its strong hierarchical nature, narrowly defined classes and lack of accommodation for intergrade soils (Butler, 1980, p.74).

The Soil Survey Staff (1975) define several diagnostic horizons in terms of the extent to which a soil has been leached, as reflected by various soil properties. Base saturation is used as a differentiating characteristic for three of the soil orders, *viz.* Alfisols, Ultisols and Mollisols.

Soils with argillic horizons are divided into two orders on the basis of base saturation. The Alfisols are distinguished from Ultisols by virtue of having a base saturation (by sum of cations at pH 8.2) greater or equal to 35%, at specific depths. Furthermore, the base saturation of Ultisols is supposed to decrease with depth, whereas the base saturation of Alfisols in supposed to increase with depth (Smith, 1983). A pH 8.2 determination of base saturation was utilized, as most analytical information available at the time had been obtained at this pH. Base saturation determined at this pH is referred to in this classification as an index of the degree of leaching (Buol *et al.*, 1989, p.89), although base saturation based upon field CEC (or effective CEC) is described as a *useful* diagnostic property of oxic horizons. Nevertheless, the meaningfulness and the use of base saturation at the great group level has been questioned, particularly with regard to the highly weathered, low CEC soils (Eswaran and Tavernier, 1980, pp.436, 439). A base saturation of 50% using the pH7 1M ammonium acetate method has been allowed to interchange with the 35% base saturation limit used to separate

Ultisols from Alfisols (Buol *et al.*, 1989, p.89).

In addition, the mollic epipedon [A horizon] is distinguished from the umbric and sombric epipedons by virtue of the mollic horizon having a base saturation (by the pH7 ammonium acetate method) greater than or equal to 50%.

Cation exchange capacity (CEC) expressed per unit mass of clay (termed apparent CEC) is used as a criterion for the kandic and the oxic horizons. Both of these horizons (expressing clay accumulation, but differing in their rate of increase of clay content with depth) result from very strong weathering so that all primary minerals, apart from quartz, have been more or less depleted. For these horizons, CEC is low and, if measured at pH7, is always less than 16cmol$_c$ kg^{-1} clay, or 12cmol$_c$ kg^{-1} clay if measured at the pH of the soil (Soil Survey Staff, 1975, p.36). For the kandic horizon only, this limit has been revised to $<$ 24cmol$_c$ kg^{-1} clay in the 1987 update (van Wambeke, 1989). Colour is generally strong because of the high amounts of Fe oxides (Duchaufour, 1977, p.169). The cambic horizon differs from the oxic in having a CEC greater than 16cmol$_c$ kg^{-1} clay at pH7. In Soil Taxonomy, the determination of CEC is used primarily to gain an indication of the dominant clay minerals present in the soil (van Wambeke, 1989).

Within the Oxisol order, acric great groups are defined as having an effective cation exchange capacity (ECEC)[5] of less than 1.5cmol$_c$ kg^{-1} clay. Eutric great groups are separated from non-eutric great groups on the basis of base saturation at 35%, by the 1M ammonium acetate displacement method.

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[5]Sum of 1M ammonium acetate exchangeable basic cations and 1M potassium chloride exchangeable acidity, expressed in cmol$_c$ kg^{-1}.

1.4.2 FAO/UNESCO classification

The widely used legend of the FAO-UNESCO "Soil Map of the World" (FAO, 1974) includes a classification and identification key. In considering indices of the degree of leaching and/or weathering, the classification system uses a base saturation of 50% (pH7 ammonium acetate) to distinguish "well-developed lessivaged ferruginous soils from less well developed lessivaged ferruginous soils" (Duchaufour, 1977, p.402). As an example, Luvisols are defined as having an argillic horizon which has a base saturation of 50% or more (by ammonium acetate) at least in the lower part of the B horizon within 125cm of the surface (Butler, 1980, p.102).

Two further soil properties, ferralic and ferric, are defined in terms of their CEC, separated at a limit of 24 $cmol_c\ kg^{-1}$ clay determined with unbuffered ammonium chloride (Lambrechts, 1990). In the definition of the ferralic B horizon, the revised FAO-UNESCO legend (FAO, 1988, discussed by van Wambeke, 1989) has now modified the expression of CEC. Previously (FAO, 1974) CEC was expressed per unit mass of clay, but now (FAO, 1988) this has been replaced by the CEC expressed per unit mass of soil. It was felt that expressing CEC in terms of clay content did not account for the contribution to the CEC by organic matter (van Wambeke, 1989). In the FAO classification(1974), the determination of CEC is used primarily to gain an indication of the dominant clay minerals present in the soil. The definition of the argic B horizon, however, for soils without a ferralic B horizon, still retains the criterion of CEC per unit mass of clay (van Wambeke, 1989). These soils are sub-divided according to CEC per unit mass of clay (considered to reflect the degree of weathering) and base saturation (the degree of leaching).

1.4.3 French classification

Duchaufour (1977, p.175) considers the French soil classification to emphasise the genetic link between different horizons within the same profile. The weathering sequence: fersiallitisation -> ferrugination -> ferrallitisation is used implicitly in the classification (Duchaufour, 1977, pp.148, 162). The soils in this sequence are separated according to the CEC expressed per unit mass of clay, so that:

fersiallitic soils have CEC (clay) >25 $cmol_c$ kg^{-1} clay;
ferruginous soils have CEC (clay) 15 - 25 $cmol_c$ kg^{-1} clay; and
ferrallitic soils have CEC (clay) <15 $cmol_c$ kg^{-1} clay.

Mollic and umbric A horizons are separated on the basis of base saturation (mollic > 50%; umbric < 50% base saturation) (Young, 1976, p.243).

1.4.4 Australian classification

Within Australia there is no universally accepted soil classification system currently in use [1989] (Buol *et al.*, 1989, p.211). One of the more recent soil classifications devised for Australian conditions has been that of Northcote (1971) and is based primarily on field-observable properties, such as colour and textural differences with depth. This classification is not considered suitable for international use (Young, 1976, p.254). The only formal use in the classification of indices reflecting the degree of weathering or leaching is with regard to soil calcareousness. Butler (1980, pp.86-88) comments that there is little philosophical or conceptual basis to the system and that the system shows little obvious patterning of soils in relation to climatic trends or geological formations of the continent.

1.4.5 South African classification

In South Africa, van der Merwe (1941 and 2nd ed. 1962) distinguished between Red Earths and Lateritic Red Earths. The Red Earths were described as fersiallitic weathering products with a high base saturation and the Lateritic Red Earths were described as ferrallitic soils with SiO_2:Al_2O_3 ratios lower than 2 which were always associated with lateritic crust or concretionary material.

Beater (1962) distinguished between ferruginous tropical soils (fersiallitic soils) and ferrallitic soils on the basis of the silica:alumina ratios, CEC and cationic saturation [base saturation]. Fersiallitic soils were considered to have a silica:alumina ratio of around 2 or slightly higher, and silica:sesquioxide ratios always less than 2, while ferrallitic soils had silica:alumina ratios of around 2 or less. Fersiallitic soils were generally regarded as having a base saturation (pH7 ammonium acetate method) greater than 40%, and ferrallitic soils a base saturation of less than 40%, with a CEC of the clay fraction below 20cmol$_c$ kg^{-1} clay. MacVicar (1965a) considers that in South Africa, ferrallitic soils occur under a MAP varying between about 860mm and 1170mm.

It was deemed desirable to separate genetically similar soils found in humid areas from those that are found in arid areas and for this reason, the base status (sum of exchangeable basic cations expressed per 100g soil) of the upper B horizon was chosen as a differentiating characteristic at the series level (van der Eyk *et al.*, 1969, p.48). In this tentative soil classification, it was recognised that the base status of the soil was not primarily intended as a measure of soil fertility (van der Eyk *et al.*, 1969, p.57). The selection of criteria in the definition of diagnostic horizons has been directed by established genetic theory (de Villiers, 1977), although Stoch (1976) disputed whether such genetic theory had been established for South Africa as a whole.

The first official definition of the degree of leaching in the southern African context was made by MacVicar *et al.* (1965)[6]. The non-calcareous soils were separated into 3 groups on the basis of the sum of extractable basic cations, *viz.* < 1.5, 1.5 - 5.0 and > 5.0 cmol$_c$ kg^{-1} soil. In a preliminary report, van der Eyk (1965b) prepared a table (Table 1) outlining soil properties that reflect the degree of leaching for upland soils.

The so-called S-value (sum of exchangeable basic cations) was preferred to base saturation as a measure of base status, as there was uncertainty at the time concerning the measurement of CEC, from which the base saturation is calculated (van der Eyk

[6]**MacVicar, C.N., Loxton, R.F.** and **van der Eyk, J.J.**, 1965. South African soil series. Part 1. Definitions and key. Soils Research Institute Report No. 107/64. Dept. Agric. Tech. Services, Pretoria. Quoted by Lambrechts (1990). The extractant is not specified.

et al., 1969, p.51).

The present system of soil classification for South Africa is a direct descendent of the system developed for the Tugela basin by van der Eyk *et al.* (1969). The definition of soil base status was extended to accommodate the influence of the clay content and led to the degree of leaching criterion defined in the official South African soil classifications (MacVicar *et al.*, 1977; Soil Classification Working Group, 1991). Class boundaries (S-value expressed per unit mass of clay) were derived from the requirement to distinguish between ferrallitic and fersiallitic soils (R.F.Loxton, pers. comm., Pretoria, July 1990).

Table 1 Degrees of leaching in upland soils, in terms of chemical properties of their B2 horizons (van der Eyk, 1965b)

	Total extractable bases (meq%)	Base saturation (%)	Reaction (pH)
Highly leached	1.5	20	4.5-5.5
Considerably leached	1.5-5.0	20-50	5.0-6.0
Moderately leached	5.0-15	50-90	5.5-7.0
Slightly leached	10-30	80-100	7.0-8.0
Hardly leached	15-30	100 (free salts)	8.0-9.0

The current soil classification system in South Africa defines the leached status of the soil in terms of the so-called S-value per unit mass of clay in the upper B horizon, where

S-value = Σ exchangeable (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) ($cmol_c\ kg^{-1}$ soil)

and

S-value per unit mass of clay = S-value x 100/clay% ($cmol_c\ kg^{-1}$ clay).

The S-value expressed per unit mass of clay is used to separate soils into three classes, *viz.* dystrophic, mesotrophic and eutrophic (excluding calcareous) soils, corresponding to markedly leached (< 5 $cmol_c$ kg^{-1} clay), moderately leached (5 to 15) and slightly or not leached (> 15).

The differentiation of topsoils by means of soil base status, as specified in Soil Taxonomy (Soil Survey Staff, 1975) was not attempted in the South African soil classification until 1977 because it would have separated genetically related materials according to van der Eyk *et al.* (1969, p.48).

While the revised South African soil classification (Soil Classification Working Group, 1991) retains the use of the S-value expressed per unit mass of clay as a measure of soil base status, in the new system the extension of the 1977 humic definition to encompass thick and thin humic topsoils with greater than 1.8% organic carbon, has had some ramifications, particularly for the soils of the Natal midlands. Soils that prior to 1991 were separated at series level by the S-value per unit mass of clay, now fall into soil forms with humic A horizons, which are not differentiated on base status. Nevertheless, while base status is not used formally for the classification of these soils, there is no reason why they may not be assigned to a non-diagnostic soil *phase* according to their base status.

In the 1991 soil classification, the following comment was made concerning the current measurement of soil base status:

> "Once sufficient data are available, it is possible that these criteria [S-value per unit mass of clay] will be replaced by percentage base saturation" (Soil Classification Working Group, 1991, p.41).

The advisability of such a change is investigated further in sections 4.1.2 and 6.4. It has also been suggested (MacVicar *et al.*, 1984) that it might be desirable to use mineralogical criteria as differentiae in the classification system, but that the obtaining of such data on a routine basis would be a problem.

1.4.6 Other systems

The **Brazilian** soil classification system (discussed in Buol *et al.*, 1989, pp.212-213) separates the well-drained tropical soils of that country into two broad classes - the Latosolic B horizon (equivalent to the oxic horizon of Soil Taxonomy) and those with textural (argillic) B horizons. The only reference found to measures of the degree of soil weathering in the Brazilian classification is that Latosolic B horizons are considered to have a CEC per unit mass of clay < 6.5$cmol_c$ kg^{-1} clay.

Some classifications, like the **Canadian** System of Soil Classification (Canada Soil Survey Committee, 1978), while considering soil properties such as carbonate content and soil reaction (pH in 0.01M $CaCl_2$), do not consider any other indices of the degree of leaching and/or weathering on any formal level in the differentiation of soils, due to the lack of strongly weathered soils in Canada, and thus there is no need for such differentiation.

The soil classification system of the **USSR** (Egorov *et al.*, 1987) recognises a strong zonal influence, and while emphasizing soil dynamics including leaching and mineral weathering and the effects of climate (Butler, 1980, p.83), does not separate soil types on the basis of measurements of the degree of leaching or weathering (other than on carbonate and salt content). The classification nevertheless does indicate *typical* values for measurements such as base saturation or unsaturation and the cation exchange capacity associated with many soil types, but the methods of determining base saturation and exchange capacity are not defined specifically in the classification system. Butler (1980, p.85) comments that in general there is not much definition built into the system and that it probably suffers from ambiguity.

Fitzpatrick's soil classification system (Fitzpatrick, 1971) is based on the observation that soils are a continuous mantle on the earth's surface and essentially defy classification (Fitzpatrick, 1971, p.106). Fitzpatrick compromises this anarchistic approach with a minimum set of assumptions, which revolve about the recognition of horizon classes and their combinations. Generalized soil classes possess sets of general characteristics of soil properties and their variability, and pedogenetic factors of soil formation, but there exist no specific examples of natural entities (Butler, 1980, p.93). With regard to the use of properties expressing the degree of leaching and/or weathering, Fitzpatrick does use CEC expressed per unit mass of clay to define certain horizons and gives typical base saturation values associated with different horizons, but these values are not diagnostic.

The Fertility Capability Classification System (FCC) (Buol and Couto, 1981) is an example of a special purpose classification with a specific objective in mind, and uses measures of soil base status in the grouping together of soils of similar fertility. The emphasis is predominantly on soil management with little regard for soil genesis. It is furthermore generally focused on the properties of the A horizon. Using the FCC as an example of a soil fertility-capability classification, the following modifiers (amongst others) of fertility classes are defined in terms of their acidity, potential for aluminium toxicity, and low CEC (or ability to supply certain essential elements). The following class modifiers are taken from Buol and Couto (1981):

Low CEC (applies only to plough-layer or surface 20cm, whichever is shallower):

$<$ 4 $cmol_c\ kg^{-1}$ soil by Σ bases + KCl-extractable Al

$<$ 7 $cmol_c\ kg^{-1}$ soil by Σ cations at pH 7

$<$ 10 $cmol_c\ kg^{-1}$ soil by Σ cations + Al + H at pH 8.2

Al toxic:

$>$ 60% EA (exchangeable acidity) saturation of CEC by Σ bases + KCl-extractable Al within 50cm

$>$ 67% Al saturation of CEC by Σ cations at pH 7

$>$ 86% EA saturation of CEC by Σ cations + Al + H at pH 8.2, or pH $<$ 5.0 in 1:1 H_2O except in organic soils.

Acid :

10-60% Al saturation of CEC by Σ bases + KCl-extractable Al within 50cm, or pH in 1:1 H_2O between 5.0 and 6.0

1.4.7 Conclusions

Soil classifications view soil properties indicative of the degree of leaching and/or weathering with different emphases. Some classifications use them as indicators of soil fertility, others as indicators of the clay mineralogy, others still as specific indices of leaching or weathering. Usually the indices are used to distinguish *between* well weathered/leached or less fertile soils, and less-weathered/leached more fertile soils, rather than to specifically determine the *extent* to which any particular soil has been weathered or leached, or its relative degree of fertility. There is no consistency, however, in the type of soil properties that are considered to reflect the extent to which such soil processes have taken place.

The essential difference between most soil classifications and most soil fertility-capability classifications is that the latter are predominantly concerned with specific soil uses, and generally focus on the topsoil, whereas most general soil classifications consider not only the solum as a whole, with particular emphasis on the subsoil, but also a wide range of possible uses and try to account for their genesis.

CHAPTER 2 METHODS OF STUDY

Introduction

There is a general consensus that the Natal midlands is an area that is ideally suited to the study of climate - soil property relationships. For example, MacVicar (1965a) describes the Natal midlands as an area in which climatic variations are clearly reflected by soil differences and that the region lends itself particularly well to the study of the climatic factor in soil genesis. Schönau and Fitzpatrick (1981) are of the opinion that the soils of the forestry zones of the Transvaal and Natal are related closely to the present-day climate of the area.

Towards this end, the state factor approach of Jenny (1941; as discussed in section 1.2) may be employed to elucidate the relationships between soil properties and indices of climate. In the establishment of such empirical relationships, it is imperative that the other soil forming factors are either reasonably constant (in the case of topography, vegetation and time), minimized (state factor man), or stratified (state factor parent material).

2.1 Assumptions and restrictions

The direct effect of climate is best seen when conditions of good drainage prevail and materials are sufficiently permeable to allow the soil solution to percolate vertically downward (Duchaufour, 1977, p.97). For this reason, poorly drained soils were not considered for inclusion in a climosequence, as factors other than climate substantially modify and often dominate the processes of soil formation.

Sites selected were those for which the soil forming factors of topography, vegetation, time and man, were sufficiently similar enough in their intensities to be regarded as constant across all sites. At each site, the parent material(s) from which soil formation occurred was noted with a view to stratification of the data set according to parent material.

Consequently, relationships studied between soil properties and indices of climate in this study apply only to the following situations, as well as they could be judged:

i) well-drained, permeable soils, formed upon a gently undulating topography;

ii) sufficiently mature soils, displaying evidence of soil maturity such as profile horizonation;

iii) uncultivated, or otherwise undisturbed (within recent history (<200 years)) sites, that have not been subjected to erosion or deposition;

iv) soils derived from the three main parent materials of the study area *viz.* shale, sandstone and dolerite;

v) the Natal midlands.

2.2 Description of the study area

The province of Natal is situated between the parallels 27° and 31° South, and is bounded on the west by the Drakensberg Mountains and on the east by the Indian Ocean. The province is characterized by a variety of physiographic features such as mountains, plateaux, plains, deeply incised river valleys, and coastal hinterlands. Phillips (1973) has separated Natal into a number of physiographic regions. Thirty-three sites in all were used in this study and occur predominantly in the upland and intermediate regions of the Natal hinterland, this being an area in which much forestry is carried out. A map of the site locations is displayed in section 2.2.5 (Figure 2). The allocation of these sites according to the physiographic regions of Phillips (1973) is as follows:

Region	No. sites
Mountain Regions	1
Plateaux Regions	1
Upland Regions	13
Basin Plainlands	2
Intermediate Regions	14
Low-lying Regions	2
Total	33

The uplands and intermediate regions of Natal may be loosely termed "the Natal Midlands" and the majority of sites used in the study (27 out of 33) fall into this area. The magisterial districts for the sites concerned are: Pietermaritzburg, New Hanover, Camperdown, Kranskop, Nkandla, Umvoti, Msinga, Richmond, Ixopo, Lion's River, Mooi River and Estcourt.

2.2.1 Climate

Natal has been described as having a warm temperate rainy climate (van der Eyk *et al.*, 1969, p.26). The climate of Natal has been well documented by Schulze (1984) and others and is strongly influenced by the physiographic features of the province. Most parts of Natal have a mean rainfall between 600mm and 1300mm per annum. Mean annual temperatures are generally between 13°C and 23°C, being higher in the dry interior river valleys, the Zululand lowveld and along the coastal belt and lowest along the Drakensberg and foothills (Dept. Agric. Tech. Services, 1974). Rain falls predominantly in the summer months.

For the study area, the climate may be described as humid to sub-humid. In some sub-regions mists are common (hence the terminology "Natal Mistbelt"), light to severe frosts may occur in winter, snow may also occur on higher ground in winter and occasional hail is recorded. Drought periods during the rainy season are not uncommon.

Selected rainfall statistics associated with each site used in the study are provided in Appendix A.

2.2.2 Geology and geomorphology

The geology and geomorphology of Natal has been documented by van der Eyk *et al.* (1969) and King (1982) and the following summary is adapted from their discussions, up-dated according to the stratigraphic column presented on the Geological Map of South Africa (Geological Survey, 1984), and the work of Partridge and Maud (1987).

The basement rocks of the province consist of contorted and metamorphosed Archaeozoic schists, gneisses and granites known as the Basement Complex and are exposed only where deep river valleys have incised into the granite belt along the axis known as the Natal Monocline (King, 1982, p.5). The Basement Complex is overlain by the Natal Group sandstones of the middle-Palaeozoic. Upon the Natal Group sandstones lies the Karoo Sequence. This Karoo Sequence is divided into a number of main groupings of successive sedimentary strata, being the Dwyka formation, the Ecca Group shales, Beaufort Group sandstones, more recent sandstone formations and basalt lava flows. The tillite of the Dwyka formation is considered to have been derived from glacial depositions of the Carboniferous Period (200 million years B.P.). This formation is overlaid by the Ecca Group of shales, comprising the Pietermaritzburg, Vryheid and Volksrust formations. Sandstones and mudstones of the Estcourt formation of the Beaufort Group succeed the Ecca Group and were themselves overlain by the Molteno, Elliot and Clarens formations of sandstones, siltstones and mudstones, and are topped by the Drakensburg basalts. Numerous intrusions of Karoo dolerite, contemporaneous with the volcanic Drakensburg basalt depositions of the Jurassic have been exposed in the Karoo Sequence. Subsequent depositions of the Cretaceous, Tertiary, Quaternary and more recent periods took place extensively over the Zululand coastal plain and other coastal areas, following the breakup of the Gondwanaland super-continent, but do not overly concern the study area of this thesis.

The stack of sedimentary strata on the Basement Complex, overlaid by the basalt lavas, has been shaped by the processes of erosion, occurring in a series of cycles, often initiated by tectonic uplift. Several mechanisms of erosion, upliftment and differential weathering have been proposed as having occurred in the Natal region and are outlined by van der Eyk *et al.* (1969), King (1982) and Partridge and Maud (1987). The standard erosion cycle of pediplanation (scarp retreat and the formation of pediments) is thought to have been the main mechanism in the creation of the present landscape.

In the Natal midlands, the dominant parent materials exposed at the surface (resulting in soil formation) are the sedimentary shales and sandstones and the igneous base-rich dolerite. For the purposes of this study, the state factor parent material was accommodated by sampling soils formed only on mature and stable landscapes, and by noting the underlying weathering rock, for stratification purposes. Those soils presumed to have been formed from colluvial, alluvial or aeolian sources, were avoided.

2.2.3 Vegetation

Acocks (1975), in a reconstruction of the vegetation pattern in A.D. 1400, considers Natal to have been wholly occupied with forest or scrub-forest in the moist regions and by bushveld in the dry or sandy regions. Moll (1976) considers the original vegetation of the Natal midlands region in particular to have been largely an open savanna of small trees with a grass understorey of primarily *Themeda triandra*, or an *Acacia sieberana* wooded grassland. This climax vegetation has, however, in many places been replaced for hundreds of years by a sub-climax vegetation of mixed grassland, resulting from and maintained by fire as the human population increased in the region. It must be noted that over much of the Natal midlands this vegetation has now been replaced, with large areas having been cleared for cultivation and for commercial afforestation with *Acacia mearnsii, Pinus spp.* and *Eucalyptus spp.*

Every effort was made to sample virgin sites, these being uncultivated or unaltered in any discernable manner. The vegetation at these sites often consisted of mixed grasses, and it was assumed that this vegetation had been present at each site for a time period sufficient to attain equilibrium with the soil at each site. For the purposes of this study, it was assumed at all sites that soil formation occurred under a constant vegetation factor associated with veld (rangeland) in good condition. The modelling of the vegetation in the water-budgeting model is discussed in section 2.3.1.1.2.

2.2.4 Soils

The forestry regions of the Natal midlands are characterized by "mature" soils which are generally freely drained, acid, with topsoils high in organic carbon (often > 2%). The subsoils are often red or yellow-brown, apedal, with medium to high clay contents and are commonly highly friable and porous. Van der Merwe (1962) terms these soils as being predominantly lateritic yellow earths and red earths. They are in general, highly leached, with accumulations of free sesquioxides. The red clay soils are commonly associated with doleritic parent material, while the yellow-brown clay soils are often considered to have been derived from the Karoo sediments (van der Eyk, 1965).

The general agricultural potential of these soils is considered to be high and Schulze (1982, pp.6-10) shows that the highly leached soils of Natal are essentially synonymous with land of high agricultural potential. Strong climatic zonality (see section 1.3.1) is evident in the landscape and is visually confirmed by the high correlation of the areas of high agricultural potential (having highly leached soils) in the Natal midlands, with the isohyetal map of mean annual precipitation (Schulze, 1982, p.13).

2.2.5 Site selection

With the objective of investigating relationships between indices of climate and soil properties in the Natal midlands, it was desirable that the sites selected could be confidently used for such research. In this regard, each site considered for inclusion in the study was subject to great scrutiny and had to conform to a number of criteria.

The initial list of potential sites was obtained from a complete listing of all weather stations in the Natal region. In this regard, the Computing Centre for Water Research (CCWR, situated on the Pietermaritzburg campus, University of Natal) holds a data base compiled, from a set of primary data from a number of organisations, by the Department of Agricultural Engineering on the same campus. This information is derived from the following sources:

i) The South African Weather Bureau;
ii) The Department of Agricultural Development;
iii) The South African Forestry Research Institute of the Department of Environment Affairs, now Forestek of the CSIR;
iv) The South African Sugar Association Experimental Station (Mt. Edgecombe); and
v) other sources, including Parks Boards, organised agriculture, municipalities, mines and private individuals.

A search of the data base was performed to identify all those climate stations in the Natal midlands that satisfied the following criteria:

i) The climate station should have a minimum of 30 years of daily rainfall data. Lynch and Dent (1990) report that 15 years of data are required in the Natal hinterland to ensure that estimates of the mean annual rainfall are within 10 per cent of the long-term mean, 90 per cent of the time. Schulze (1989) advises that twice that length of record (i.e. 30 years) is desirable for the operation of a daily water-budgeting model, such as ACRU.

ii) The climate station must not have a MAP inconsistent with neighbouring stations or topography (any such stations are routinely highlighted on the CCWR database, although this delineation is not fool-proof[7]);

iii) The climate station must not have more than 5 months of zero recorded rainfall over the entire data span, during the wettest 3 months of the year (any such stations are also routinely highlighted on the CCWR database and are attributed to poor reporting from the station);

iv) For all remaining stations, the ratio of complete data years to the record span in years was calculated by the writer. This ratio is considered by the writer as an indication of the 'degree of completeness' or 'reliability' of the rainfall record. Thus as a further basis for screening, all those stations with an arbitrary ratio of less than 0.70, were excluded, *viz.*:

$$\frac{\text{Complete data years}}{\text{Record span (years)}} < 0.70$$

This ratio is used by the writer as an index of station 'quality'. The lower the ratio, the greater the risk of the data poorly representing the station's long-term rainfall record, and the greater the proportion of the rainfall record that will have to be synthesized to fill in missing information for the purposes of modelling.[8]

After the data base search had been completed and stations had been excluded or accepted according to the above criteria, 119 climate stations were found to satisfy the above criteria in the Natal midlands, as at July 1990 (although not all were visited).

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[7]For example, the site at Muden (29°03'S 30°22'E) is reported to have a mean annual rainfall of 1010mm based upon a 56 year average, a figure which is incompatible with the arid nature of the soils and vegetation of the region. This station was not incorporated into the climosequence.

[8]For example, as at January 1991, on the CCWR database, Qudeni Forestry station is reported to have 43 years of daily rainfall data over a record span covering 1939 to 1989, being 51 years, giving a ratio of 0.84.

Of the sites that were visited, not all were found to be ideal for the climosequence study. The presence of saprolite throughout the profile, the influence of man, obvious erosion and deposition, excluded such sites from consideration. Where possible, farmers and managers present at the sites were questioned about possible soil disturbances in the past, such as ploughing or fertilizer applications.

A total of 33 sites was selected for the Natal midlands climosequence, a summary of which is provided in Table 2. Full site information is detailed in Appendix A. For the set of sites, the mean number of years of daily rainfall data was 48.1 years. The mean MAP for the set of sites is 915.4mm, ranging from a lowest figure of 618mm (Inadi) to the highest of 1524mm (Qudeni). The location of the sites is indicated on a map of the study area in Figure 1.

2.2.6 Soil sampling

When a site was deemed to meet the above conditions for inclusion in a climosequence, several auger holes were sunk in the vicinity of the raingauge to find a place for a suitable pit to be dug. These auger soil samples established in the field the presence of saprolite, degree of soil disturbance and a general indication of soil variability. A suitable and representative pit was then dug, or on occasions where a fresh cutting was present, the cutting was exposed back into the bank by approximately 50cm. The profile was then morphologically described according to the South African Soil Classification (Soil Classification Working Group, 1991). Soil samples were taken incrementally down the profile, usually at intervals of 10cm and the occurrence and positions of all horizons and sub-horizons were noted. Where possible, samples from all four walls were taken for each separate soil depth and bulked. Profile descriptions for the sites used in the climosequence and analytical data for the soil samples, are presented in Appendix A.

Table 2 Summary of sites selected in the Natal midlands

Station	Lat. (S)	Long. (E)	Alt. (m)	Data span 19xx to 19xx		Years of data	MAP* (mm)	Reliability Index†
Bloemendal	29°32'	30°28'	838	1952	1989	38	898	1.00
Windy Hill	29°30'	30°34'	960	1932	1989	53	998	0.91
Cedara	29°32'	30°17'	1067	1914	1989	75	877	0.99
Dargle	29°32'	30°01'	1280	1953	1989	33	965	0.89
Ixopo	30°09'	30°04'	1029	1932	1989	46	787	0.79
Little Harmony	29°56'	30°19'	810	1937	1989	53	891	1.00
Richmond	29°52'	30°16'	884	1916	1989	62	980	0.85
Baynesfield	29°45'	30°20'	808	1927	1989	49	799	0.78
Cramond	29°24'	30°26'	762	1919	1989	69	968	0.97
Hawkestone	29°22'	30°18'	1075	1921	1989	67	1204	0.97
Rambleholm	29°26'	30°23'	671	1916	1961	32	794	0.70
Mooi River	29°13'	30°02'	1371	1928	1989	62	715	1.00
Westfield	29°21'	30°04'	1375	1947	1989	42	1015	0.98
Knight	29°24'	30°04'	1400	1929	1981	52	1026	0.98
Nutfield	29°27'	30°05'	1200	1953	1989	35	1043	0.95
Glen Eland	29°02'	30°56'	1050	1932	1989	55	957	0.95
Linklater	28°58'	30°54'	1097	1948	1989	38	903	0.90
Kranskop	28°58'	30°51'	1173	1932	1989	51	870	0.88
Inadi	28°51'	30°41'	863	1913	1982	50	618	0.71
Gem	29°03'	30°39'	1010	1941	1982	40	801	0.95
Boscombe	29°04'	30°49'	1140	1928	1989	56	1079	0.90

Table continued over page

* - Mean annual precipitation calculated after correcting for missing data
† - Reliability Index: Complete daily data span (years)/Record span (years)

Table 2 continued:

Station	Lat. (S)	Long. (E)	Alt. (m)	Data span 19xx to 19xx		Years of data	MAP* (mm)	Reliability Index†
Eston	29°52'	30°31'	792	1922	1989	57	711	0.84
Qudeni	28°39'	30°53'	1524	1939	1989	43	1559	0.84
Ntabamhlope	29°02'	29°39'	1490	1958	1988	31	1098	1.00
Highmoor	29°19'	29°37'	1981	1955	1989	31	1275	0.89
Camperdown	29°43'	30°33'	762	1914	1989	61	699	0.80
Freeland	30°15'	30°15'	914	1959	1988	30	955	1.00
Springbrook	30°15'	30°10'	1066	1939	1988	48	746	0.96
Stae Braes	30°00'	30°11'	411	1926	1979	45	650	0.83
Inglenook	29°52'	29°53'	1280	1957	1988	30	823	0.94
Lilydale	30°00'	29°58'	1330	1947	1986	38	770	0.95
Bray Hill	29°10'	29°53'	1524	1952	1989	36	858	0.95
Kilmoshogue	29°10'	29°52'	1520	1909	1989	79	875	0.98

* - Mean annual precipitation calculated after correcting for missing data
† - Reliability Index: Complete daily data span (years)/Record span (years)

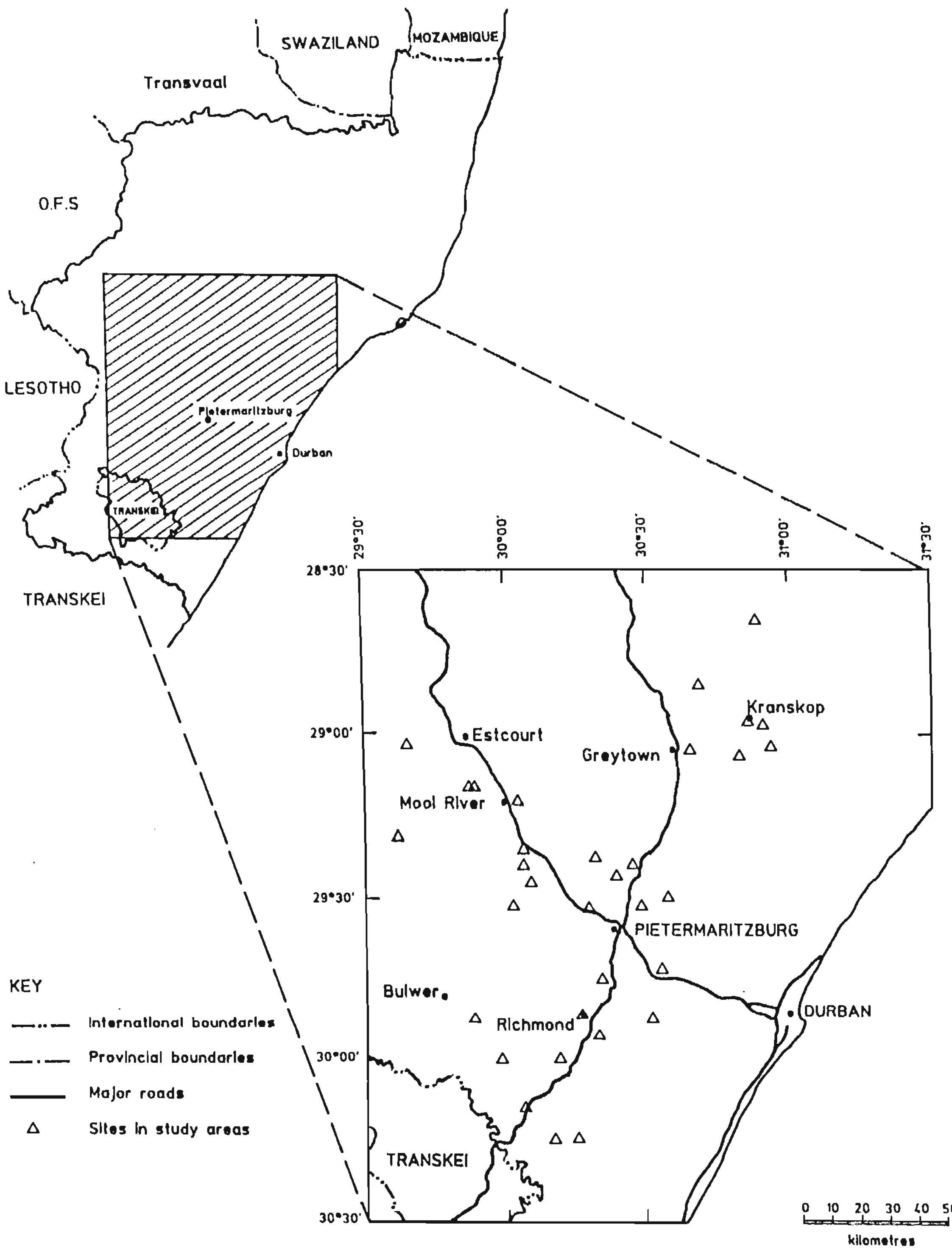

Figure 1. Map of the Natal midlands showing the location of sites used in the climosequence.

2.3 The modelling of climate

In the establishment of soil property-climate relationships, it must be assumed that, although the general climate of the region in which the comparison is being made may have differed historically from the present climate, the climate at each site has not changed *relative to all other sites within the region*. This assumption is not unreasonable for such modelling purposes and it has been observed by Blosser and Jenny (1971) in a Californian context that:

> " ..many soil properties are in accord with present day climate. Either climate has not changed significantly, in a pedological sense, for a long period of time; or the soil properties of past climatic regimes have adjusted themselves to today's environment; or past climates are highly correlated with present-day climates".

In a study of clay mineralogical changes within a climosequence in South Africa, van der Merwe and Weber (1965) have suggested that the soils have formed under specific climatic conditions and that no marked changes have taken place during their evolution. As mentioned before, Schönau and Fitzpatrick (1981) consider the soils of the forestry zones to be closely related to present-day climate.

Furthermore, it must be assumed that the historic climatic data available on a daily basis are representative of the climate under which the soil was formed. It must be noted that the output from such a model will at best be of a relative nature, given the bias introduced in the measurement of input data, particularly rainfall, even under "normal" conditions, as discussed in Schulze (1989) and Schulze (in Scholes and Savage, 1989).

While a choice of several water budgeting models existed, for this particular study, for determining relevant indices of climate, such as drainage from the soil profile and for estimating the long-term effective rainfall at a site, the decision as to which model to use was conditioned by the availability of climatic information in a format amenable for direct input into any particular model. On the Pietermaritzburg campus of the University of Natal, both an agrohydrological water-budgeting model (ACRU-2), with associated expertise and a large database of climatic information in the appropriate format for the ACRU model was accessible and is in regular use at the Computing Centre for Water Research (CCWR). Considerable reformatting of climatic information would have been necessary for any other water-budgeting model and was not undertaken.

2.3.1 The ACRU model - a brief description

The ACRU-2 agrohydrological model developed in the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg is a versatile model that can simulate the soil water budget and total evaporation processes (Schulze, 1989) under a range of conditions and for numerous applications. It incorporates parameters for soil type, vegetation type and rooting characteristics. It may thus be used to determine the relative and average amounts of soil water movement, and the relative mean annual effective rainfall at different sites, given adequate and comparable long-term rainfall and temperature data as input. This model has been verified successfully against observed data sets from different countries, including soil moisture data from field plots, lysimeters and catchments (Schulze, 1986; Dent, 1988).

The concepts behind the ACRU-2 modelling system, its input requirements, usage and on-going refinements have been well documented (Schulze, 1984, 1986, 1989; Schulze and George, 1989). ACRU-2 may be used to model the soil water budgeting cycle on a daily basis in terms of a multi-layer soil horizon approach. It is a multi-optional model and may be run at varying degrees of complexity, depending on output requirements and available input information. Its general structure is illustrated in Figure 2.

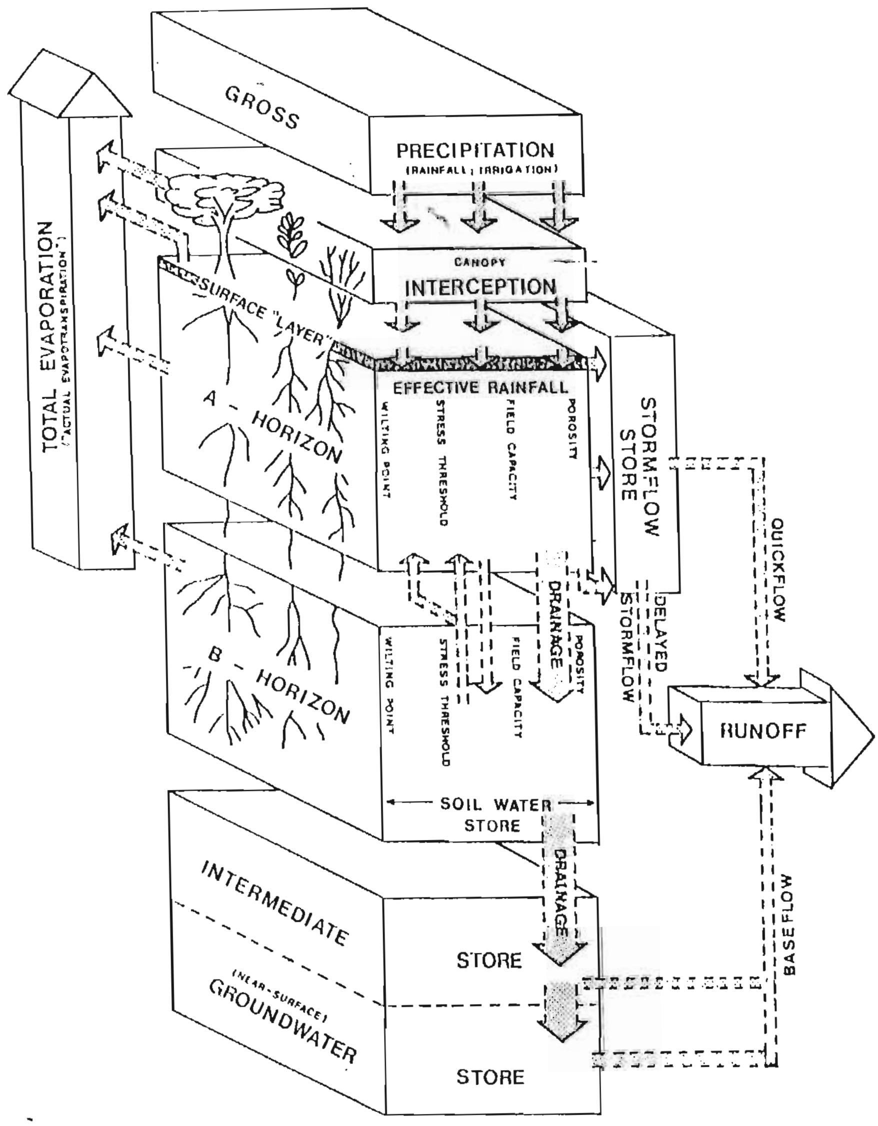

Figure 2. The ACRU-2 agrohydrological modelling system: general structure (Schulze, 1989).

2.3.1.1 Modelling inputs

The water-budgeting model ACRU-2, described in section 2.3.1, was employed. The following information was collected to run the model:

2.3.1.1.1 Climatic data

Daily rainfall data and monthly means of daily maximum and minimum temperature were input directly. Where daily rainfall data sets were incomplete, the missing daily values were synthesized according to the technique of Zucchini and Adamson (1984), using data from nearby stations, taken from a set of approximately 2500 stations throughout South Africa, which were selected as controls for patching missing data. The monthly temperature information was discretized to daily values through the use of Fourier analysis within the model.

2.3.1.1.2 Vegetation

All sites considered were characterised by veld (rangeland) in good condition, as discussed in section 2.2.3. Default values for the coefficient of initial abstraction, crop coefficient, monthly proportion of roots in the A horizon and canopy interception loss for veld (rangeland) in good condition were taken from information provided in the ACRU-2 users' manual (Schulze *et al.*, 1989b).

2.3.1.1.3 Soils information

Each profile sampled was assumed to be modal for the site. For each profile, permanent wilting point and field capacity of the soil horizons were estimated from laboratory derived values according to the equations of Hutson (1984) and Schulze *et al.* (1985), and soil porosity figures related to textural classes were extracted from tables provided by Schulze (1989a). Critical stormflow response depths are related to the A horizon depths and soil texture as discussed in Schulze (1989b).

2.3.1.1.4 Potential Evaporation

Potential evaporation was estimated according to the Linacre (1984) equation (discussed in Schulze, 1989b) which uses monthly means of daily maximum and minimum temperatures to generate monthly evaporation converted within ACRU-2 to daily values by Fourier analysis, with corrections made for rainy and rainless days. A check on the input/output at each site was made according to the points listed by Schulze *et al.* (1989b). As an initial check, runoff simulation values from ACRU-2 were compared against regional values mapped by Midgley *et al.* (1983). Where possible, mean daily wind speed data were calculated for the various sites from a Department of Agriculture publication entitled "Summary of Climatic Conditions in Natal: March 1984". In the absence of reliable wind speed data for any particular site, a default value of 1.2 ms^{-1} was used (Schulze *et al.*, 1989b).

2.3.1.2 Modelling outputs

At each site, mean annual precipitation (MAP), mean annual effective rainfall (MAER), and mean annual drainage (MAD) (from the B1 horizon, and from the 50cm depth) was calculated (MAD[B1] and MAD[50cm] respectively).

2.3.1.2.1 Mean annual precipitation (MAP)

Mean annual precipitation (MAP) was calculated from the daily rainfall figures after missing values were simulated according to the technique of Zucchini and Adamson (1984) (see section 2.3.1.1.1). An examination of the rainfall statistics for each site (Appendix A) reveals that annual precipitation approximates a normal distribution, with no marked difference between the mean and median values at each site.

2.3.1.2.2 Mean annual effective rainfall (MAER)

Information for this variable (defined by Schulze (1989b) as: gross precipitation less interception, stormflow and deep drainage) is generated by the model on a daily basis. A mean annual value for effective rainfall (MAER) was calculated, excluding the first year of data (as the model is initialized with a default soil water status that may not be a true reflection of the actual situation). Like annual precipitation, annual effective rainfall approximates a normal distribution, with no marked difference between the mean and median values at each site (see Appendix A).

The standard errors of estimation of the means and the coefficients of variation (CV%) associated with the annual effective rainfall series at each site are lower than those associated with the annual precipitation series at each equivalent site. In other words, for a given series of rainfall data, there should be greater confidence in the sample MAER being closer to the long-term (or population) MAER, than there is of the sample MAP being close to the long-term MAP. This result is not surprising as the modelling process dampens the influence of extreme rainfall events by taking runoff and the buffer of soil water storage into account.

2.3.1.2.3 Mean annual drainage (MAD)

The monthly summary output option of the ACRU-2 model provides information about the soil water draining though the base of the B horizon, i.e. the lower horizon of the root zone. The rate at which soil water held in the soil above field capacity is assumed to drain into the B horizon and to groundwater is dependent upon soil texture and is varied in the model according to soil type. By specifying varying depths for the B horizon within the model, the amount of soil water draining though any sub-horizon or depth within the B horizon may be approximated. In this manner, mean drainage through the B1 horizon of the soils considered, as well as mean drainage from the 50cm depth, were simulated with ACRU-2. Mean and median values were taken for all the years for which data were generated, again excluding the first year of data for the reason outlined in section 2.3.1.2.2.

Annual profile drainage out of the B1 horizon and annual drainage from the 50cm, generally have distributions that are noticeably skewed to the left (as shown by the positive standardized kurtosis values in Appendix A). This positive skewness becomes particularly apparent with the drier sites. An examination of the statistics, however, for these drainage variables exposes the very unstable nature of this output, reflected by the very large values for the coefficients of variation at all sites. This is as a result of the highly influential effect of abnormally wet periods in the data sets. For this reason the use of a median value for drainage may be a more stable and a less easily influenced statistic in the description of soil leaching.

Of interest was the variation of mean annual drainage as a function of soil depth. As an exercise, four sites had the drainage from incremental sub-horizons within each profile simulated, by varying the soil depth in the model at which drainage out of the root zone is presumed to occur. The mean soil water movement profiles for the four selected sites were then constructed (Figure 3). This distribution pattern bears a close resemblance to related distributions generated by Arkley (1963) for more generalized soil cases in arid regions of North America.

For these Natal midlands sites, it would appear that there is an exponential decline in soil water movement with soil depth in the "drier" areas and a more linear decline with soil depth in the "wetter" areas. It is evident that the mean amount of soil water draining out of the root zone on an annual basis is highly dependent upon the specified soil depth. Given the high subjectivity associated with the determination of the B1 and other sub-horizons in a profile, the use of a modelling approach of this nature may be best suited to a comparison of soil properties with respect to a median annual soil water drainage at a specified and constant absolute soil depth, for all sites used in a comparison.

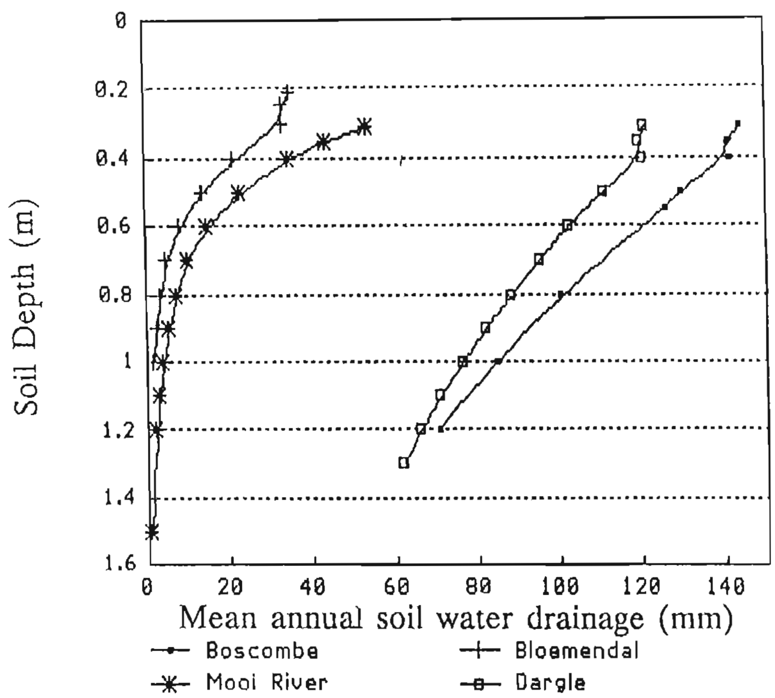

Figure 3. Mean soil water drainage with respect to soil depth at four sites in the Natal midlands.

2.3.1.2.4 Correlation between indices of climate

The question arises: to what extent does the modelling process modify or vary indices of climate? A correlation matrix, for all 33 sites, was constructed to shed light on this question:

n=33

MAP	1.00					
MAER	0.94	1.00				
MAD [B1 drainage]	0.84	0.81	1.00			
median B1 drainage	0.83	0.78	1.00	1.00		
MAD [50cm drainage]	0.86	0.82	0.98	0.98	1.00	
median 50cm drainage	0.85	0.79	0.96	0.96	0.97	1.00

All correlations are highly significant ($p < 0.01$).

It would appear that all the indices of climate, while differing in magnitude, are highly related to each other. The correlation matrix shows that the correlation between mean and median drainage from the B1 is 1.00 and that between mean and median drainage from a constant 50cm depth in the profile is 0.97. Consequently there is no benefit in selecting median over mean annual drainage and for the purposes of this study, the use of mean annual drainage is retained. The relationships between MAP, MAER and MAD [B1 horizon], are displayed in Figures 4 and 5.

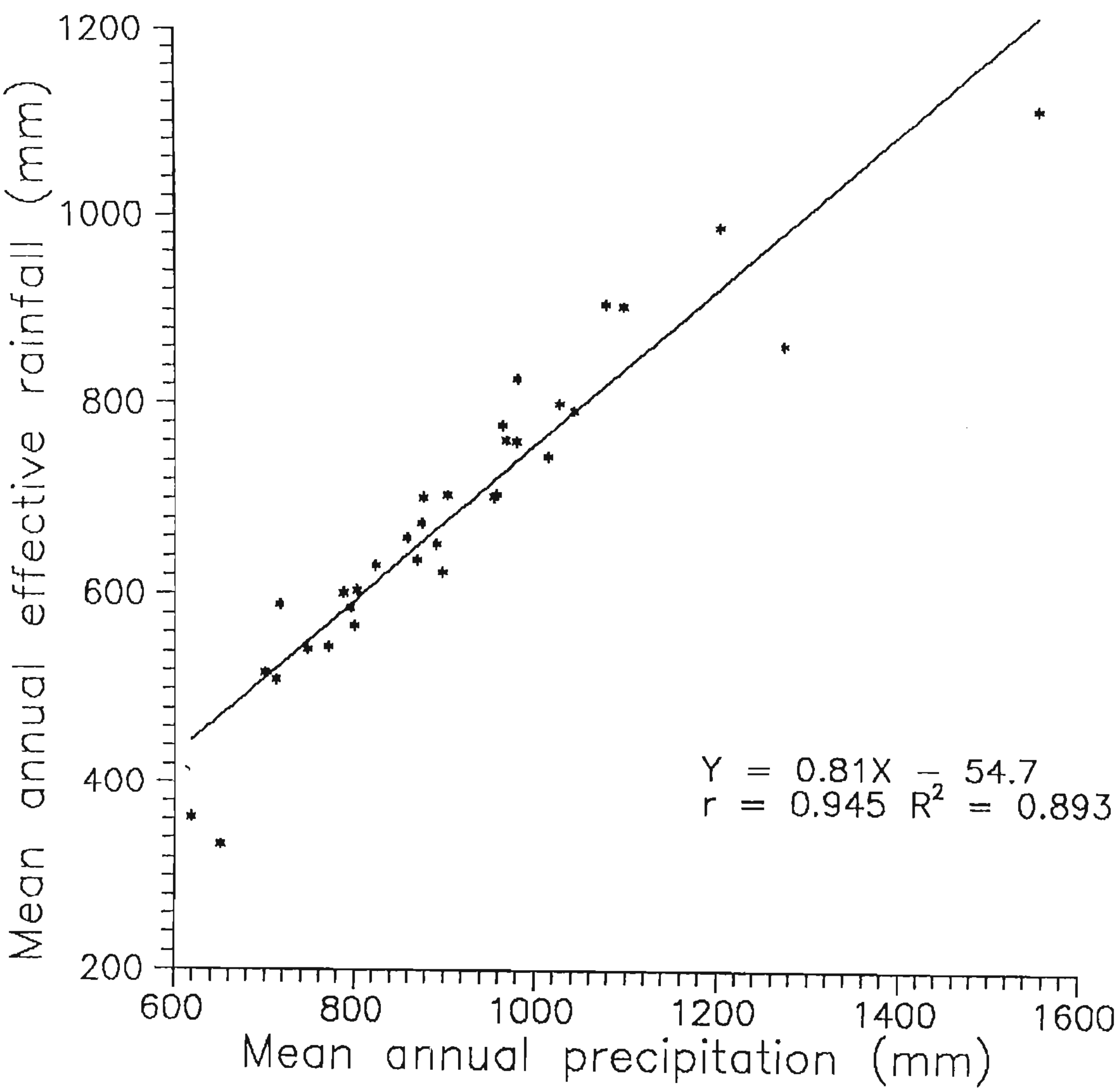

Figure 4. Relationship between mean annual precipitation and mean annual effective rainfall for 33 sites in the Natal midlands.

For a region in California, Jenny *et al.* (1968) have also noted a very high correlation (0.997) between MAP and another index of climate, being Arkley's leaching index, *Li* (which is determined by subtracting each monthly mean potential evapotranspiration from each mean monthly precipitation, and summating all those months with positive values (Arkley, 1963)).

It would appear that within the more restricted region of the Natal midlands, climate is largely related to the magnitude of the mean annual precipitation, and is relatively independent of the other climatic modifiers, such as temperature, evapotranspiration and water runoff, used in the calculation of MAER and MAD[B1].

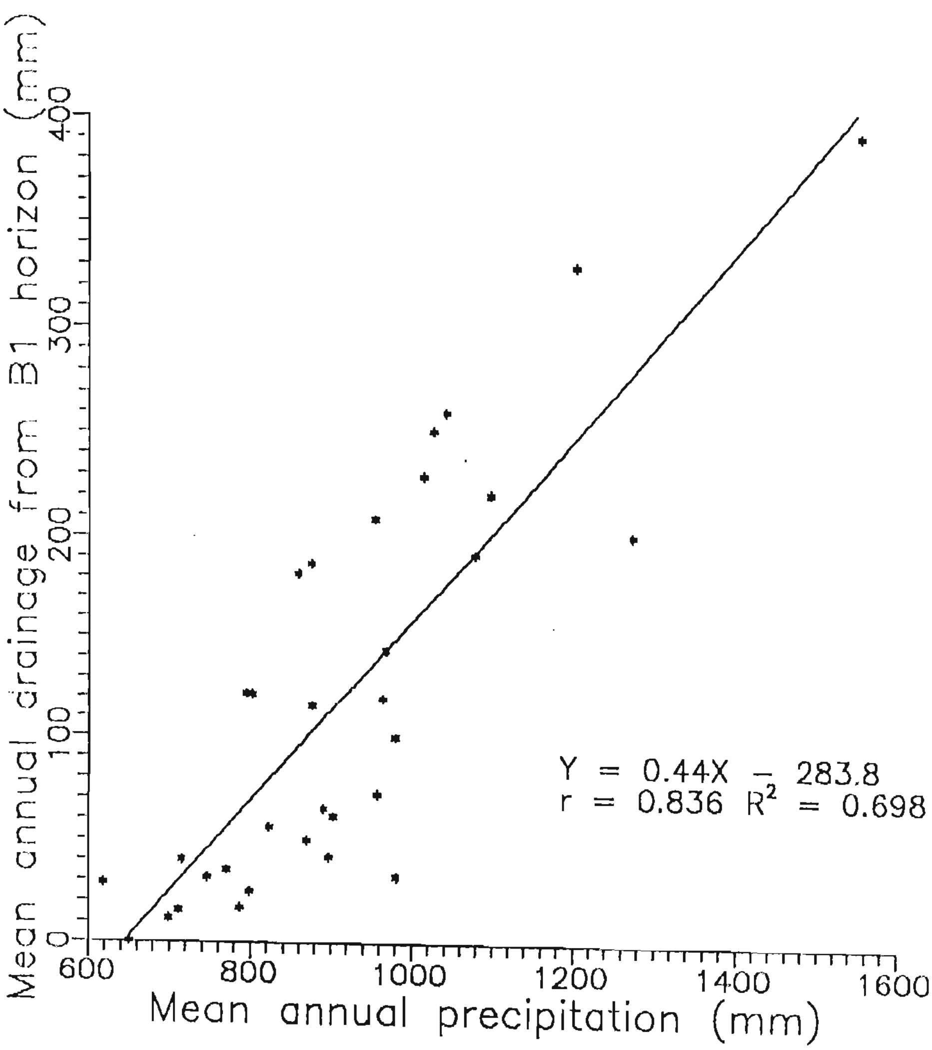

Figure 5. Relationship between mean annual precipitation and mean annual drainage out of the B1 horizon for 33 sites in the Natal midlands.

2.4 Soil analysis

The study of climate - soil property relationships required that soil properties indicative of the extent to which leaching and/or weathering of the soil have occurred, be characterized. In accordance with the considerations of sections 1.3 and 1.4, soil properties representing cation exchange characteristics, soil surface area, soil acidity, total elemental concentrations, soil solution composition and organic matter were sought. Towards this end, the following soil properties were determined:

2.4.1 Soil chemical characteristics

Exchangeable basic cations: 1M pH7 ammonium acetate exchangeable basic cations Ca^{2+}, Mg^{2+}, K^+ and Na^+ determined by atomic absorption/flame emission spectrophotometry. The sum of these exchangeable basic cations expressed in $cmol_c\ kg^{-1}$ is termed the S-value.

Exchangeable acidity: unbuffered 1M potassium chloride exchangeable acidity (Al^{3+} and H^+) determined by titration against a standardized sodium hydroxide solution, and expressed in $cmol_c\ kg^{-1}$.

Effective Cation Exchange Capacity (ECEC): the sum of exchangeable basic and acidic cations (S-value and exchangeable acidity) expressed in $cmol_c\ kg^{-1}$.

Base saturation: calculated as the proportion of the ECEC that is occupied by the exchangeable basic cations, expressed as a percentage.

Soil acidity (pH): pH determined in a slurry of 10g soil in 25cm^3 deionized H_2O, 1M KCl and 0.01M $CaCl_2$, and expressed as pH (H_2O), pH (KCl) and pH ($CaCl_2$) respectively.

Loss-on-ignition (LOI): the thermogravimetric mass lost upon ignition of a soil sample at 430°C (Donkin, 1991), expressed as a percentage of the oven dry (105°C) soil mass.

Walkley-Black Organic Carbon: the readily oxidizable organic carbon fraction determined by the wet oxidation of organic matter using potassium dichromate/sulphuric acid (Walkley, 1947).

Soil organic nitrogen: determined by the Kjeldahl method, the sulphuric acid digestion of organic nitrogen to ammonium sulphate, with a subsequent determination of ammonium ions, using selenium as a catalyst (FRI Bulletin no.70, 1984, p.13).

C/N ratio: determined as the ratio of Walkley-Black organic carbon to soil organic nitrogen as determined by the Kjeldahl method.

Bray-2 exchangeable P: a mixed extractant (Bray-2), being 0.03M NH_4F in 0.1M HCl, was used to extract P from soils, and the exchangeable P was determined colorimetrically using the molybdate blue method (Bray and Kurtz, 1945).

Total elemental concentrations: the total major elemental concentrations of Si, Al, Fe, Mn, Mg, Ca, Na, K, Ti, P, Cr and Ni were determined spectroscopically by XRF, and expressed in terms of the oxide percent of the non-volatile (1000°C) soil fraction.

Soil solution analysis: performed on two separate soil solution equilibria, these being a 1:2 soil:deionized water solution and a 1:5 soil:0.01M $CaCl_2$ solution. Solution Si was determined according to the silicomolybdous blue procedure (Hallmark *et al*., 1982) on both sets of solutions, and expressed in terms of the negative logarithm of the silicic acid activity pH_4SiO_4. Electrical conductivity (EC), followed by pH were also determined on the 1:2 soil:water solution set according to the methodology of Rhoades (1986).

2.4.2 Soil physical characteristics

Soil texture: described in percentage terms of the clay (<0.002mm), silt (0.02-0.002mm) and sand (2mm-0.02mm) fractions of the soil, in accordance with textural triangle of the 1977 soil classification (MacVicar *et al.*, 1977). Soil samples were pre-treated with hydrogen peroxide (30% v/v) and the size fractions were determined by the sedimentation and pipette method (Day, 1965) after treatment with sodium hexametaphosphate and sodium carbonate and ultrasonic dispersion.

Specific surface area (SSA): determined by the ethylene glycol monoethyl ether (EGME) retention method (Carter *et al.*, 1986) and expressed in m^2g^{-1}.

Details of all analytical methods used are provided in Appendix B.

CHAPTER 3 CHARACTERIZATION OF LEACHING AND WEATHERING AND THE COVARIANCE OF SOIL PROPERTIES

Introduction

The processes of leaching and weathering are the principal means by which the action of climate as a soil forming factor is manifested in well-drained soils (see sections 1.3.2 and 1.3.3). It is therefore important, before embarking on the study of the *actual* relationships between individual soil properties and indices of climate (Chapter 4), that an understanding of the concepts of leaching and weathering and their interaction is gained. In addition, an investigation into the covariance that exists between many soil properties indicative of leaching and weathering may lead to a more selective and directed search for relationships between soil properties and indices of climate.

In this chapter, these concerns are addressed in three stages:

i) the concepts of leaching and weathering and their interactions are defined and discussed in terms of their relationships with the state factor climate (section 3.1);

ii) a study of the covariance found in some selected soil properties from four data sets is undertaken using multivariate statistics (section 3.2); and

iii) the relationships *between* indices of the degree of leaching and indices of the degree of weathering are investigated (section 3.3).

3.1 The concepts and definitions of leaching and weathering

For well-drained, porous soils, leaching and weathering are soil processes directly related to climate (Duchaufour, 1977, p.97). In this section, the meaning of the terms *leaching* and *weathering* and their interaction is examined.

3.1.1 Leaching

Leaching has been defined as the translocation of soluble salts along with percolating soil water during drainage (Ross, 1989, p.112). In all soils, to greater or lesser extents, leaching is accompanied by cheluvation (the translocation of organometallic complexes or chelates) and lessivage (the translocation of colloidal clay particles) (Ross, 1989, p.110). Leaching is also called *lixiviation* by Duchaufour (1977, p.68) and is defined by him as the migration of soluble salts [out of the soil profile].

The rate of the leaching process may be considered to be influenced by several factors, these being:

i) the total amount and distribution of precipitation (rainfall);
ii) soil structure, texture, and porosity;
iii) topography, vegetation, and the depth and duration of ground frost (Ross, 1989); and
iv) soil temperature, in determining the effectiveness of rainwater in dissolving minerals (Fanning and Fanning, 1989, p.324).

The pore-size distribution, pore continuity and structural attributes of soils greatly influence water movement, chemical transformation and consequently the leaching potential. Unfortunately, the quantification of soil physical characteristics of this nature is notoriously difficult and in general many assumptions are made with regard to these aspects of soil physical behaviour.

The gradual loss of the alkali (Na^+ and K^+) and alkaline earth cations (Ca^{2+} and Mg^{2+}) leads to their replacement on the exchange complex by protons (H^+) and Al^{3+} ions. This leads to a gradual acidification of non-calcareous profiles and a lowering of the base status of the whole profile (Duchaufour, 1977). Duchaufour (1977, p.68) states that

> "Re-adsorption of cations in the B-horizon can occur, but the general balance indicates a deficit, particularly in a humid climate with a strong element of climatically controlled drainage. The movement of generally

> very mobile soluble salts favours the process of subtraction from the whole of the profile (that is to say losses by drainage) rather than redistribution between the A and B horizons; this is a fundamental aspect of lixiviation."

A leaching sequence is observed, with the soluble salts being 30-100 times more mobile than the exchangeable basic cations, which are in turn 5-10 times more readily leached than silica (from non-quartz origins), and non-quartz silica is 5-10 times more mobile than quartz and the sesquioxides (Young, 1976, p.71). As will be seen in section 3.1.2, this sequence may also be considered as a weathering sequence.

To maintain an ionic balance, anions also accompany cations in the process of leaching. These anions may be inorganic, such as nitrate or bicarbonate, or organic, such as lactate (Duchaufour, 1977, p.68).

In the assessment of a soil's degree of leaching, traditional measures of soil base status may be used as a point of departure. These measures include base saturation, and the sum of basic cations (the so-called S-value) expressed per unit mass of clay.

3.1.2 Weathering

Ollier (1984, p.1) defines weathering as:

> "..the breakdown and alteration of materials near the earth's surface to products that are more in equilibrium with newly imposed physico-chemical conditions."

The term "weathering" encompasses both physical and chemical weathering. Physical weathering is largely concerned with the mechanical breakdown of the parent material, and in the process exposes a larger surface area to further weathering mechanisms.

In pedological terms, however, the concept of weathering, in the humid and sub-humid regions, is principally concerned with the chemical weathering processes. These processes have been traditionally viewed using either (i) chemical thermodynamics and kinetics; (ii) measurements of soil constituents relative to the unweathered parent material; or (iii) the mass balance approach using catchment and streamwater solute budgets (Ross, 1989, p.6). Of these approaches, the thermodynamic approach requires a large number of assumptions, has many uncertain equilibrium constants and is generally concerned with simple, ideal, equilibrium based, closed systems, and in effect does not yet adequately describe the complex interactions occurring in soil (see section 1.1; also Ross, 1989, p.35). The catchment/streamwater mass balance studies of approach (iii) are generally only able to represent gross trends within a region. As a result, in the determination of an index of weathering, pedologists have usually resorted to the classical measures of the relative amounts or ratios of soil constituents to the same constituents in the parent material, this being approach (ii). Such weathering indices include the silica:alumina ratio ($SiO_2:Al_2O_3$) and the silica:sesquioxide ratio ($SiO_2:R_2O_3$) of the clay fraction, although there are numerous related weathering indices.

The degree of weathering is considered to be a measure of the extent to which minerals have undergone transformation and in consequence, progression along a clay-size weathering sequence. Implicit in most of these discussions is the importance of the clay fraction of the soil. In the 1950's, an estimate of the degree of weathering was reached by consideration of the mineralogical inventory of a soil, but such approaches tended to neglect the interactions occurring between clay minerals and the soil solution, as well as the state factors of parent material and time (Herbillon, 1981, pp.80-86).

Surface properties of clay minerals, such as the cation exchange capacity (CEC) expressed per unit mass of clay, or the effective cation exchange capacity (ECEC) (sum of basic and acidic cations on the exchange complex, determined at a pH which approximates field pH for variable charge soils (Juo *et al.*, 1976)) are commonly regarded as properties distinguishing the degree of weathering (Herbillon, 1981, p.86) and are reported to have a great number of associated properties which are useful in a soil management sense. Herbillon (1981, p.91) describes measures of the degree of weathering, based upon surface properties of soils, as being especially suited to the description of soils in the later stages of weathering, when the bulk chemical and mineralogical compositions of the soils show little further change. Young (1976, p.95) regards the CEC expressed per unit mass of clay as an indication of the nature of the clay mineral when only standard analytical data is available.

The degree to which a soil has undergone weathering may also be reflected by the concentration of silicic acid present in the soil solution. The silica potential (pH_4SiO_4) of the soil solution is directly dependent upon the clay mineral suite (Garrels and Christ, 1965, p.352). This index of weathering puts the emphasis upon the supply of silica rather than on the depletion in the concentration of exchangeable bases used in CEC measurement.

There have been alternative soil properties considered to be indices of the degree of weathering, such as: abrasion pH (Grant, 1969; Ferrari and Magaldi, 1983); the degree of Fe fractionation (Bäumler *et al.*, 1991); the pedogenic crystallinity of kaolins (Hughes and Brown, 1979; Hughes, 1980); and the silt:clay ratio (Young, 1976, p.88). These properties are relatively rarely used, and certainly not to the same extent as CEC or the classical molecular metal oxide ratios, and are consequently not pursued in this thesis.

3.1.3 The interaction of the leaching and weathering processes

The relationship between the degree of leaching and the degree of weathering in well-drained soils, has been the focus of some debate (Crompton, 1960; Papadakis, 1962; Dan and Singer, 1973; Young, 1976, pp.68-82).

In the differentiation of major soil groups, Crompton (1960) has demonstrated that weathering and leaching may be considered as distinctly different processes which do not necessarily vary directly or equally with any environmental variation, or with each other, and has drawn up a conceptual diagram with the indices of leaching and weathering on separate axes (Figure 6).

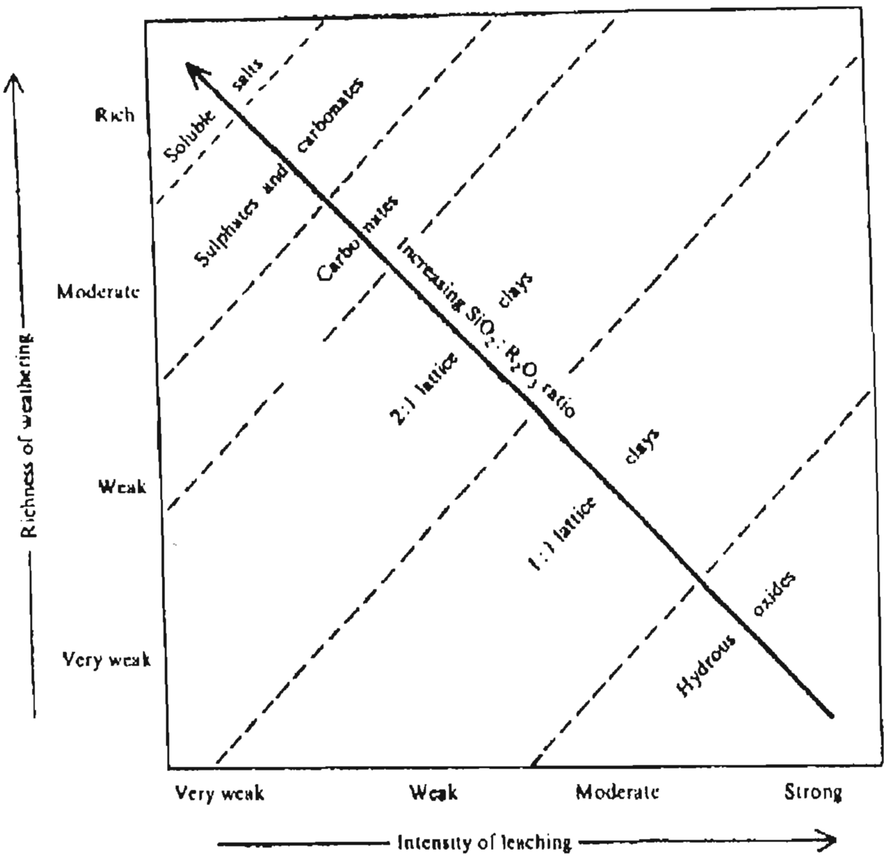

Figure 6. Plot of the general relationship between the degree of weathering and the degree of leaching, with the superimposed silica:sesquioxide ratio line (adapted from Crompton, 1960), for freely drained soils with limited influence of mor humus.[9]

Papadakis (1962) distinguishes between the degree of leaching and the degree of weathering in terms of the impact on soil fertility; weathering makes a pool of nutrients more available for plants to utilize, whereas leaching translocates such nutrients from the soil profile.

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[9]It is worth noting that the *richness of weathering* axis of Crompton (1960) describes the *potential* of a soil to undergo weathering, and thus is the reverse of the more common *intensity of weathering* axis, where it is the extent to which weathering has occurred, which is being described.

Young (1976, p.68), however, contends that the processes of leaching and weathering cannot be wholly separated. The release of elements by weathering determines the extent to which they are removed by leaching, and the intensity of leaching, through its removal of constituents from the weathering matrix, determines the secondary materials that are formed. The leaching processes are thus regarded by Young as being interposed between the two components of weathering, being the breakdown of primary minerals, and the formation of secondary minerals. Thus in well-drained soils, chemical weathering is enhanced by leaching, due to the flushing of the reaction products from the weathering zone. In terms of le Chatelier's principle of equilibrium, this will tend to promote further weathering and therefore leaching aids and abets the weathering processes, and neither process is independent of the other. Dan and Singer (1973) say that many soil scientists consider leaching to be an integral part of the weathering process, with the proviso that the water-holding capacity of a soil may modify the relationship between leaching and weathering.

3.2 A study of the covariance of selected soil properties

That many soil properties (chemical, physical, biological, mineralogical and morphological) exhibit covariance is well-known, and in the process of selecting properties as criteria for classification or for the study of pedogenesis, there are obvious advantages in being able to focus on a sub-set of properties which carries a high content of information. In particular, various indices of leaching are determined from a number of individual soil properties which are all highly related and covariant with one another. An examination of the covariance present in any set of related data of this nature may therefore lead to the development of a more elegant expression of the relationships between properties which depend for their intensity of expression upon the degree of leaching of the soil.

The rationalization of soil data of this nature is best suited to some form of multivariate analysis and to this end, correlation analysis, principal component analysis, factor analysis and cluster analysis have all been used (Sarkar *et al.*, 1966; Arkley, 1971;

McNeal *et al.*, 1985; Little and Smith, 1986; Mellor, 1987; Ovalles and Collins, 1988; Litaor *et al.*, 1989). In particular, factor analysis is suited to the determination of a set of descriptive concepts which summarize the relationships among components of a system of interrelated variables (Mather, 1976).

3.2.1 Materials and methods

This particular study was based on the analytical data for 130 samples taken from 102 soil profiles. Fifty-three of these soils were documented by van der Eyk *et al.* (1969). The remaining 49 soils were sampled at different locations in the Natal midlands. The basis for selecting soils was that they should occur in areas of high enough rainfall to qualify them for consideration in afforestation programmes and that they should be well drained (absence of diagnostic horizons signifying wetness). A summary of the three groups of sets of soils is given in Table 3.

The Comrie data were obtained from soil samples taken from pits on a transect through a toposequence of soils derived from dolerite and shale. Each sample represented a composite from the four walls of the soil pit at different depth intervals, down to 120cm or to saprolite. Analytical data were calculated as mean values for the profile as a whole, weighted according to the thickness of the horizon which each sample represented. The soils were of clayey texture, generally mesotrophic, and belonged to the Magwa, Inanda, Kranskop or Glenrosa forms (Soil Classification Working Group, 1991).

The Tugela Basin data can be found in the Appendix of van der Eyk *et al.* (1969). The basis for selection was that the soils should have yellow or red apedal B or red structured B horizons, as defined by van der Eyk *et al.* (1969). The data for the B2 or, where specified, the B21 horizon (equivalent to the B1 horizon of the 1991 classification) were used.

The Natal midlands data sets were obtained from the climosequence described in section 2.2.5. In this case, data for the A and upper B (B1) horizons were considered separately.[10]

Table 3 Summary of the three groups of soils used for factor analysis.

Origin	No. of profiles	Sampling	No. in analytical data sets
Comrie plantation, Donnybrook	21	Whole profile	21, representing weighted means for profile according to depth
Natal midlands	28	A horizon	28
		upper B	28
Tugela basin	53	B horizon (B2 or B21)	53

For the Comrie and Natal midlands soils, the following were determined: silt and clay concentration by the pipette method (Day, 1965) after a 3 minute ultrasonic treatment of 10g H_2O_2-pretreated soil with 10cm^3 sodium hexametaphosphate solution; Ca^{2+}, Mg^{2+}, K^+ and Na^+ extractable with neutral, 1M ammonium acetate; 1M KCl extractable acidity titrated against 0.001M NaOH; pH in a slurry of 10g soil in 25cm^3 deionized H_2O, 1M KCl and 0.01M $CaCl_2$; organic carbon by wet oxidation (Walkley, 1947); and loss on ignition (LOI) at 600°C (Comrie soils) or 430°C (Natal midlands soils). That two different temperatures were used for ashing is not expected to make a significant difference to the multivariate analysis since there is a high correlation

[10]This work was carried out at an earlier stage in the research programme, and as such reflects work done on only 28 out of the final 33 sites used in the remainder of the study, and is published as **Donkin, M.J.** and **Fey, M.V.**, 1991. Factor analysis of familiar soil properties of some Natal soils with potential for afforestation. *Geoderma* 48: 297-304. It was not felt that the addition of the remaining five sites to this particular statistical analysis would have altered the conclusions reached, especially as the factor analyses concerned were carried out on four sets of data, of which two were drawn from A and B horizons from the 28 Natal midlands sites.

between LOI values determined at these two temperatures (Donkin, 1991). Two indices of base status were calculated: base saturation (sum of basic cations as a percentage of sum of basic cations and exchangeable acidity) and the S-value/100g clay (calculated as the sum of bases expressed per unit mass of clay). Details of these analytical methods are provided in Appendix B.

The analytical data from the Tugela Basin study were similar to the above, except that they did not include LOI, or pH measured in KCl and $CaCl_2$ solutions, but did include organic nitrogen concentration which had not been determined for the Comrie or Natal midlands soils at the time. Base saturation was calculated as the sum of basic cations expressed as a percentage of cation exchange capacity (determined by ammonium ion saturation of the exchange complex).

In all cases where soil properties are a direct summation or subtraction of other soil properties (e.g. sand (%) = 100 - (clay + silt)), these soil properties were not included in the analyses in order to allow matrix inversion to take place in the calculations.

Individual factor analyses of the four data sets were performed using the Statgraphics software (STSC, Inc., 1986). In all cases, soil properties were standardized to zero mean and unit variance in order to obtain homogeneity of variance. Correlation matrices were calculated and the principal components derived from these were subjected to an orthogonal rotation of axes procedure (varimax rotation) to obtain a factor analysis. The best number of factors to extract for rotation is not determined especially for small-sample data sets (Mather, 1976; Digby, 1991, *pers. comm.*). In this study 5 factors were extracted in each factor analysis since this number of factors generally accounted for most of the total variance. The loading (or eigenvector) of a variable on a factor is akin to the correlation between the variable and the factor (McNeal *et al.*, 1985). Properties that have a large loading on the same factor are considered to be covariant and the varimax-rotation procedure is designed to reduce the number of variables that exhibit a high loading on any one factor in order to simplify interpretation.

3.2.2 Results

The results of the factor analyses on the four sets of data are presented in Tables 4 and 5. To aid in the clarity of the tables and in the interpretation of factors, only those factor loadings with an absolute value greater than an arbitrary value of 0.250 are shown. Significance values for loadings do not exist (McNeal *et al.*, 1985). The first five factors accounted for 89.9% of the total variance in the Comrie set; 88.7% in the Natal midlands A horizon set; 90.5% in the Natal midlands B horizon set; and 89.5% in the Tugela basin data set.

Table 4 Factor analysis results showing the relative loadings of variables on 5 factors derived by varimax rotation for soil sets from Comrie, Natal midlands A horizons, and Natal midlands B21 horizons, respectively.

Comrie profile weighted mean set

Soil Property	Factor Loadings 1	2	3	4	5
clay %	-0.428	0.806			
silt %		-0.859			0.366
LOI		0.484	0.780		-0.275
organic C %			0.938		
pH (KCl)	0.612	0.444	0.388	0.270	-0.311
pH (H_2O)	0.556	0.368		0.624	
pH ($CaCl_2$)	0.802	0.339		0.285	
Exch. Ca	0.888				
Exch. Mg	0.861			0.288	
Exch. K					0.961
Exch. Na	0.327			0.920	
Exch. acidity	-0.882	0.257			
Base saturation %	0.915				
S-value/100g clay	0.897	-0.270			
% of total variance	45.2	22.3	10.2	7.7	4.5

Table 4 cont.

Natal midlands A horizon set

Soil Property	Factor Loadings 1	2	3	4	5
clay %					0.972
silt %			0.860		
LOI			0.903		
organic C %			0.918		
pH (KCl)	0.865	0.268			
pH (H_2O)	0.897	0.326			
pH ($CaCl_2$)	0.901	0.324			
Exch. Ca	0.542	0.775			
Exch. Mg		0.803		0.440	
Exch. K	0.327	0.590			
Exch. Na				0.935	
Exch. acidity	-0.752		0.337		0.421
Base saturation %	0.740	0.524			
S-value/100g clay	0.280	0.868			-0.299
% of total variance	48.3	15.8	11.7	7.5	5.4

Natal midlands B21 horizon set

Soil Property	Factor Loadings 1	2	3	4	5
clay %					0.946
silt %			0.880		
LOI			0.781	-0.352	0.365
organic C %		-0.348	0.838		
pH (KCl)	0.719	0.656			
pH (H_2O)	0.718	0.480			
pH ($CaCl_2$)	0.803	0.555			
Exch. Ca	0.962				
Exch. Mg	0.774			0.512	
Exch. K	0.787	0.404			
Exch. Na				0.932	
Exch. acidity		-0.843	0.311		
Base Saturation %	0.452	0.662		0.449	
S-value/100g clay	0.944				
% of total variance	48.2	16.6	10.1	8.6	7.1

Table 5 Factor analysis results showing relative loadings of variables on 5 factors derived by varimax rotation for B2 horizon soils from the Tugela basin study.

Soil Properties	Factor Loadings				
	1	2	3	4	5
clay %	0.335	0.756			0.285
silt %					0.917
organic C %	-0.259	0.872			
organic N %	-0.252	0.820		0.282	
pH (H_2O)	0.785		0.464		
Exch. Ca	0.948				
Exch. Mg	0.839		0.448		
Exch. K				0.965	
Exch. Na	0.403		0.864		
Base saturation %	0.823	-0.307			-0.253
S-value/100g clay	0.861		0.366		
% of total variance	46.3	20.8	9.3	8.2	4.9

In the case of the Comrie data, Factor 1 is most strongly aligned with measures of soil base status and soil acidity; Factor 2 with soil texture; 3 with soil organic matter; 4 with exchangeable Na^+ and pH (H_2O); and 5 with exchangeable K^+.

In the data set for the A horizon soils from the Natal midlands, Factor 1 was again aligned most strongly with base status and acidity parameters; 2 with base status; 3 with silt content and organic matter; 4 with exchangeable Na^+ and to a lesser extent, Mg^{2+}; and 5 with clay content.

For the B horizons of these Natal midlands soils, Factor 1 was once again aligned with soil base status and acidity; Factor 2 with soil acidity and some components of base status; 3 with silt content and the organic matter; 4 with exchangeable Na^+; and 5 with clay content.

In the Tugela Basin data set, Factor 1 was aligned with soil base status and acidity; 2 with soil organic matter and clay content; 3 with exchangeable Na^+ and pH(H_2O); 4 with exchangeable K^+; and 5 with silt content.

3.2.3 Discussion and conclusions

Several observations and conclusions could be drawn from the patterns of covariance which emerged from the factor analyses.

(i) *Exchangeable cations and base status*. The covariance between exchangeable K^+ and Na^+ and other parameters of soil base status was generally low. This may have partially been due to analytical considerations. Concentrations of Na^+ and K^+ are usually much smaller than those of Ca^{2+} and Mg^{2+} so that there is more chance that any covariance with the overall base concentration will be masked by error. Furthermore the common release of additional extractable K^+ by drying, the more so in soils with low K^+ contents (Haby *et al*., 1988), indicates that air-drying may reduce the variance of exchangeable K^+ across different soils and also that K^+ behaviour is inherently different from that of other basic cations. Such deviance is usually attributed to the presence of unweathered mica (Swindale and Uehara, 1966) although Levy *et al*. (1988) have shown that kaolinite and kaolinitic soils may exhibit a similar effect. It was also observed by Verma *et al*. (1987) in a study of highly weathered soils that there was an inverse relationship between both exchangeable Ca^{2+} and Mg^{2+} and rainfall, but no clear relationship between exchangeable K^+ and rainfall. Therefore, to the extent that exchangeable basic cations can be employed for calculating an index of degree of leaching there seems to be a case for excluding exchangeable K^+. In the case of Na^+, its relatively low concentration, weak degree of adsorption on cation exchange surfaces and its possibly frequent recharge in areas with an oceanic influence on precipitation all suggest that there would be little to gain from its inclusion in an estimate of total exchangeable bases. A strong case seems to exist for the exclusion of the exchangeable monovalent cations K^+ and Na^+ from the calculation of a soil index used for the prediction of the effective rainfall of a site.

(ii) *pH and base status*. In those instances where comparison was possible, the pH measured in 0.01M $CaCl_2$ consistently exhibited a higher loading with soil acidity/base status factors than did pH in H_2O or 1M KCl. This probably vindicates the original suggestion by Schofield and Taylor (1955) that ionic strength of the soil solution in the field needs to be simulated quite closely for pH measurement to be meaningful.

(iii) *Silt and organic matter.* The silt fraction and soil organic matter were frequently aligned with the same factor. This suggests that the clay-aggregating effects of humus were incompletely destroyed by H_2O_2 treatment. As might be expected (Goldin, 1987; Donkin, 1991) the organic matter content showed a high degree of covariance with loss on ignition, confirming the utility of the latter measurement when laboratory convenience is a consideration.

(iv) *Clay.* Only in the Comrie data set are clay concentration and exchangeable acidity contrasted with the other properties in Factor 1. This may reflect a more youthful character of many of the soils in this set, in which an earlier stage of weathering might be expected to result in an inverse relationship between clay content and base saturation. In other data sets there was less indication of any strong covariance between clay content and other properties except loss on ignition and silt content.

(v) *Comparison of A and B horizons.* No noteworthy differences were observed between the factor analyses of the data for A and B horizons from the same profiles (Natal midlands set). This corroborates the findings of Iriarte Mayo *et al.* (1988), who have shown that factors obtained separately for A and B horizon soils in the Guadix-Baza basin in Spain, are very similar to each other.

In conclusion, factor analysis was found to be an attractive tool in the elucidation of relationships between commonly measured chemical and physical properties in well-drained Natal soils. For the four sets of data, factors associated with soil acidity or base status and texture accounted for most of the variance in all cases. The exchangeable monovalent cations K^+ and Na^+, however, were generally out of alignment with factors related to base status. The covariance of soil pH measured in

0.01M $CaCl_2$ with factors related to base status was consistently higher than that for pH measured in water or 1M KCl. These results therefore provide some additional degree of quantitative justification for the selection of certain properties as differentiae in soil classification. Relationships between climatic indices and soil properties that are calculated from the exchangeable cations, may be improved by the exclusion of the monovalent cations from the calculation of such soil indices.

3.3 The relationships between degree of leaching and degree of weathering

The interdependence of the leaching and weathering processes in general, has already been discussed in section 3.1.3. It is of interest to examine the extent to which some common measures of the degree of leaching and the degree of weathering are covariant, for soils of the Natal midlands. Such covariance will not only reflect the extent to which the two processes may be considered to be dependent on each other in this region, but also the extent to which measures of such properties may reflect both processes. Given the multivariate character of soil data, factor analysis was again employed (as in section 3.2) to clarify such relationships.

3.3.1 Materials and methods

Soil samples were taken from the B1 horizons of each of the 33 sites used for the Natal midlands climosequence detailed in section 2.2.5. The following soil properties were determined: the neutral 1M ammonium acetate exchangeable basic cations Ca^{2+}, Mg^{2+}, K^+ and Na^+; unbuffered 1M potassium chloride extractable acidity titrated against 0.001M sodium hydroxide; clay content by the pipette method (Day, 1965) after a 3-minute ultrasonic treatment of 10g of H_2O_2 treated soil with 10cm^3 of sodium hexametaphosphate solution; silicic acid concentration in the soil solution, using a 1:2 soil:water ratio, Si determined using the silicomolybdous blue procedure (Hallmark *et al.*, 1982) and expressed as pH_4SiO_4; the molecular oxide concentrations of Si, Al Fe and Ti were determined by XRF spectroscopy; pH in a slurry of 10g of soil in 25cm^3

of deionized water, 1M KCl and 0.01M $CaCl_2$; loss on ignition (LOI) at 430°C (Donkin, 1991); organic carbon by wet oxidation (Walkley, 1947) and organic nitrogen by the Kjeldahl digestion method (FRI Bulletin no.70, 1984, pp.13-20). From these analyses, the following composite soil properties were calculated: the S-value per 100g of clay (being the sum of exchangeable basic cations expressed per unit mass of clay); the effective cation exchange capacity (ECEC) expressed per unit mass of clay (sum of the exchangeable basic cations and exchangeable acidity expressed per 100g of clay); base saturation (sum of basic cations as a percentage of ECEC); the silica:alumina (SiO_2:Al_2O_3) and silica:sesquioxide (SiO_2:R_2O_3) ratios of the soil clay fractions *relative to the equivalent respective ratios of the parent materials from which each soil was derived*; and the titanium oxide content relative to the titanium oxide content of the parent material from which each soil was derived[11]. Details of analytical methods are provided in Appendix B.

As an initial exercise, a correlation matrix was constructed using two soil properties that may be considered to represent the degree of leaching (S-value per 100g clay and base saturation) and three soil properties that have been considered to represent the degree of weathering (ECEC per 100g clay; pH_4SiO_4; and the silica:alumina ratio of the clay fraction, relative to the equivalent ratios of the parent materials from which each soil is derived).

Factor analysis of the data was performed using the Statgraphics software (STSC, Inc., 1986). All soil properties were standardized to zero mean and unit variance to obtain homogeneity of variance. Principal components derived from a correlation matrix were subjected to an orthogonal rotation of axes procedure (varimax rotation) to obtain a factor analysis. Using similar arguments to those expressed in section 3.2, five factors were extracted for rotation.

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[11]Mean parent material metal oxide ratios were calculated from data obtained from "Analyses of rocks, minerals and ores", Geological Survey, Pretoria, 1964. See also Appendix D.

3.3.2 Results

The relationships between the five indices of leaching and weathering are presented in the form of a correlation matrix:

correlation matrix (n=33):

1	S-value per 100g clay	1.00				
2	Base saturation %	0.43*	1.00			
3	ECEC per 100g clay	0.94***	0.48**	1.00		
4	pH_4SiO_4	-.47**	-.18	-.62***	1.00	
5	§$Si:Al_{clay}/Si:Al_{rock}$	0.19	0.35*	0.32	-.54**	1.00
		1	2	3	4	5

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

§ - $SiO_2:Al_2O_3$(clay)/$SiO_2:Al_2O_3$(parent material)

It is evident that a considerable degree of covariance exists amongst these variables. In particular, it would appear that ECEC expressed per 100g clay, an index of weathering, is statistically significantly correlated with the other indices of leaching and weathering (with the exception of the silica:alumina index), but that the linear relationships between the other indices are not so clear. Factor analysis was again employed and the results are presented in Table 6.

As in section 3.2, five factors explain most of the variance in the data set (90.7%) and were subjected to an orthogonal rotation of axes procedure (varimax rotation). Again, only those loadings with an absolute value greater than an arbitrary value of 0.250 are shown, to aid in the interpretation and clarity of the factor analysis (Table 6).

The first factor may be interpreted as an 'soil acidity' factor, as it has high loadings for pH measured in all three electrolytes and for base saturation, with lesser loadings for the ECEC variables and the S-value per 100g clay. The second factor may be loosely described as a 'base status' factor, having high positive loadings for the S-value per 100g clay, ECEC, ECEC per 100g clay and a moderate negative loading for pH_4SiO_4. Factor 3 is largely concerned with the metal oxide ratios, and also has a moderate negative loading for pH_4SiO_4. Soil organic matter components are strongly aligned with Factor 4, and Factor 5 is dominated by the clay content loading.

Table 6 Factor analysis results showing the relative loadings of variables on 5 factors derived by varimax rotation for B1 soil samples taken from well-drained sites from around the Natal midlands.

Natal midlands B1 horizon set

Soil Properties	Factor Loadings 1	2	3	4	5
S-value/clay	0.415	0.872			
Base sat %	0.843		0.252		
ECEC	0.406	0.876			
ECEC/unit clay	0.356	0.892			
pH_4SiO_4		-0.623	-0.608		
§$Si:Al_{clay}/Si:Al_{rock}$			0.955		
Φ$Si:R_{clay}/Si:R_{rock}$			0.940		
•TiO_2			-0.684	0.427	
clay %					0.965
pH (KCl)	0.809	0.424	-0.327		
pH ($CaCl_2$)	0.889	0.394			
pH (H_2O)	0.880				
C %				0.921	
N %				0.908	
LOI %		-0.274	-0.346	0.741	0.338
% of total variance	37.7	24.3	13.6	10.2	4.9

§ - $SiO_2:Al_2O_3$(clay)/$SiO_2:Al_2O_3$(parent material)
Φ - $SiO_2:R_2O_3$(clay)/$SiO_2:R_2O_3$(parent material)
• - TiO_2(soil)/TiO_2 (parent material)

3.3.3 Discussion and conclusions

The factor analysis shows that there is a clear distinction between those properties that reflect soil acidity, soil base status (founded on clay surface properties) and the metal oxide ratios, as evidenced by the first three factors, respectively. It is also of interest that the soil organic matter properties and the clay content occur on factors 4 and 5 respectively, and do not contribute significant loadings to the first three factors. A possible interpretation may be that clay content and organic matter concentrations are not in themselves good indicators of soil acidity, soil base status or the metal oxide ratios.

The discussions of section 3.1 indicate that there are no definitive soil properties that can be considered to measure the degree of leaching or the degree of weathering and that properties used for such purposes are generally imposed. Nevertheless, if the S-value per 100g clay may be used as an index of the degree of leaching (Soil Classification Working Group, 1991), and the silica:alumina ratio of the clay fraction (relative to the silica:alumina ratio of the parent materials from which each soil was derived) may be used as an index of the degree of weathering (Jenny 1980, p.332), then these two indices may be contrasted graphically, as in Figure 7.

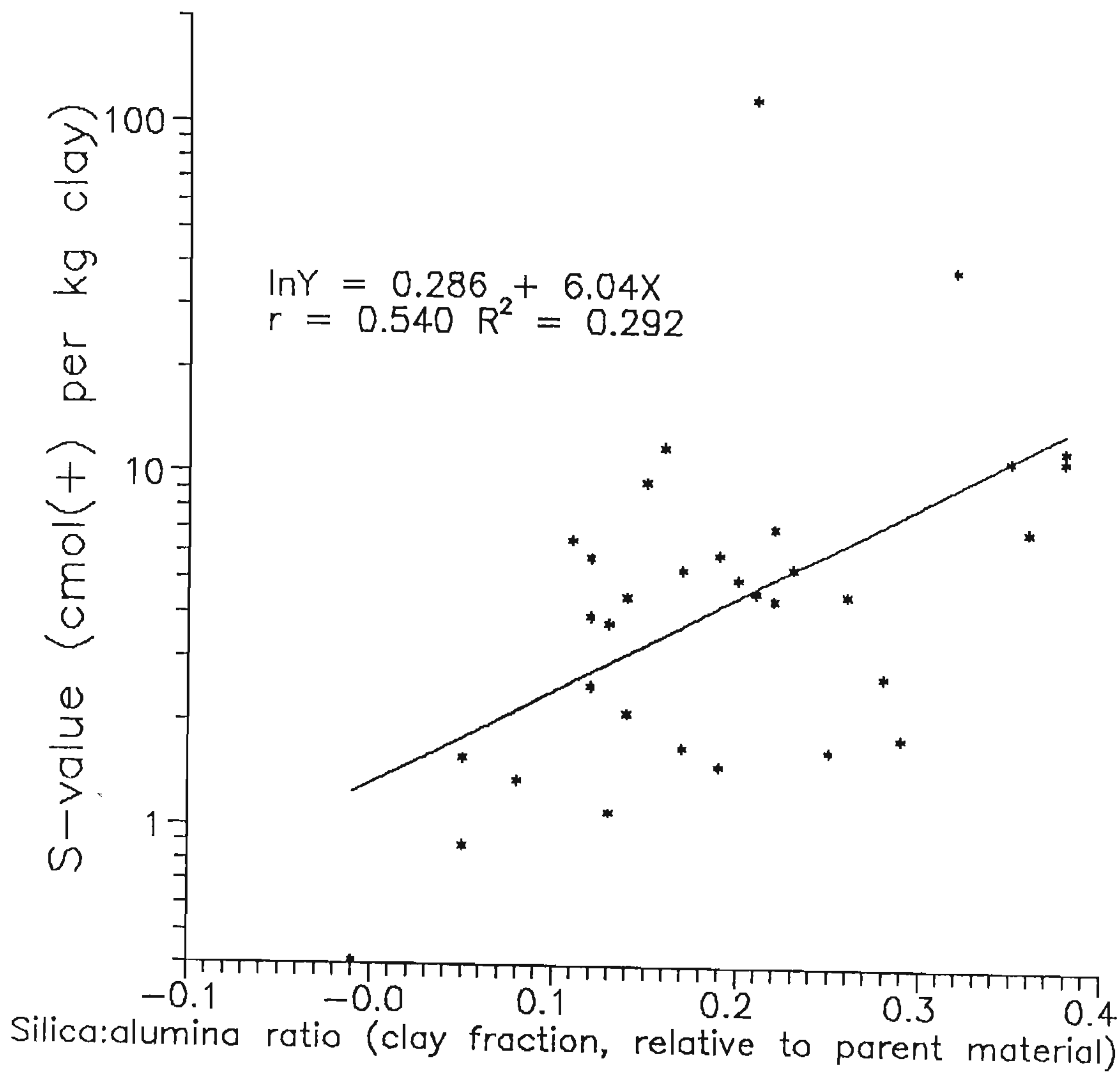

Figure 7. Plot of an index of the degree of leaching (S-value per unit mass of clay), against an index of the degree of weathering (silica:alumina ratio of the clay fraction, relative to the original ratio of the parent material).

A statistically significant relationship ($p<0.05$) between these indices of leaching and weathering is obtained ($r = 0.540^*$). This would tend to indicate that the concepts of the degree of leaching and the degree of weathering, while not to be thought of as synonymous or necessarily causal, are nevertheless inextricably interrelated and this supports the contentions of Young (1976, p.68).

The results of the factor analysis would tend to confirm the supposition that no one soil property or index can be said to definitively and intrinsically specify the degree of leaching or the degree of weathering of a soil. The factor analysis (Table 6) indicates that there is a web of related and covariant soil properties ranging from acidity/exchange properties to surface/clay mineral properties to the elemental and proportional composition of the clay fraction. It remains to be seen how these soil properties are individually related to indices of climate. This is the subject of the next chapter.

CHAPTER 4 RELATIONSHIPS BETWEEN SOIL PROPERTIES AND CLIMATIC INDICES IN THE NATAL MIDLANDS

Introduction

Given the wealth of accumulated analytical data and the vast number of possible combinations and permutations thereof in relation to the climatic indices, it was deemed appropriate to focus on that sub-set of relationships that is germane to the objectives of this study. Graphs and detailed statistics have only been provided for those relationships of special importance, but most relationships are summarized in the form of correlation matrices.

Furthermore, the detailed description of selected relationships between soil properties and indices of climate are restricted here, in the main body of the thesis, to those concerning the B1 soil properties. Relationships obtained between climatic indices and soil properties relating to (i) A horizons, and (ii) samples taken at a constant depth of 50cm, did not generally result in an improvement over the relationships obtained with B1 samples and climatic indices discussed here. Correlation matrices similar to those presented in the following discussions, for properties of the A horizon samples, the 50cm depth samples and for further soil properties of the B1 horizon, are given in Appendix C.

In all cases where relationships are presented, the use of a particular scale or transformation may be taken to imply that other scales or transformations (such as quadratic, reciprocal or logarithmic) resulted in an inferior fit of the data. Common transformations of variables in all cases were attempted, especially where such transformations were expected in theory. Of the few studies that have attempted to quantify the rates of soil formation or transformation, most indicate that exponential - or conversely logarithmic - functions are obtained (Yaalon, 1975; Sondheim *et al.*, 1981), in accordance with chemical kinetics and most weathering studies.

Either individual soil properties (eg. pH) or compound expressions (eg. base saturation) were related to climatic indices. The simultaneous selection of numerous soil properties in multiple regressional fits of data sets was not actively pursued for the following reasons:

i) most soil properties are highly covariate and the concurrent selection of several of these variables often results in equations that are unstable in the sense that if a change in one soil property is not balanced by changes in other soil properties, the predictive ability of such an equation becomes tenuous, or less robust;

ii) the use of alternatives such as principal component analysis in multiple regression, while providing orthogonal data matrices, creates an artificial barrier between the regression equation based on the principal equations and the soil system described by the variables (Page, 1976), and will not necessarily increase understanding (Jenny, 1980, p.324). The more complex an equation becomes, the less "meaningful" or accessible it becomes to the layman who has to use it;

iii) the greater the number of soil properties that need to be determined, the greater the time and the cost become in the acquisition and treatment of such data;

iv) at all times such investigations are guided by the principle of Ockham's razor. In essence this states that a more complex solution of any problem should only be sought if simpler solutions are not found to be satisfactory. Thus a simple, pragmatic and meaningful relationship between indices of climate and soil properties is sought, even at the possible expense of some predictive precision.

4.1 Indices of leaching

4.1.1 S-value per unit mass of clay

The soil classification system currently in use in South Africa (Soil Classification Working Group, 1991) defines the leached status of the soil in terms of the so-called S-value, expressed per unit mass of clay in the B1 horizon, where:

S-value = Σ exchangeable Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} ($cmol_c\ kg^{-1}$ soil)

and

S-value per unit mass of clay = S-value x 100/clay% ($cmol_c\ kg^{-1}$ clay).

The S-value expressed per unit mass of clay separates non-calcareous soils into three classes, *viz.* dystrophic, mesotrophic and eutrophic, corresponding to strongly leached (< 5 $cmol_c\ kg^{-1}$ clay), moderately (5 to 15) and slightly leached (> 15).

For the 33 sites from the Natal midlands, the relationship between the S-value expressed per unit mass of clay and mean annual precipitation (MAP) is displayed in Figure 8. A logarithmic scale is used for the S-value per unit mass of clay axis, as there is a better linear relationship between $\log_e$(S-value per unit mass of clay) and MAP, than with other transformations of the S-value per unit mass of clay. MAP explains 55% of the variance in the S-value per unit mass of clay.

Linear model: lnY = a + bX

Dependent variable - Log_e (S-value per unit mass of clay)

Independent variable - Mean annual precipitation (MAP)

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	5.3399	0.6425	8.3109	<0.0001
Slope	-0.004251	0.000688	-6.1767	<0.0001

Analysis of Variance (ANOVA):

Source	Sum of Squares	Df	Mean Square	F-ratio	Prob.level
Model	20.86102	1	20.86102	38.152	<0.0001
Error	16.95051	31	0.54679		
Total (Corr.)	37.8115	32			

Correlation coefficient = -0.7428
Standard error of estimation = 0.7395cmol$_c$ kg^{-1} clay
R^2 = 0.5517

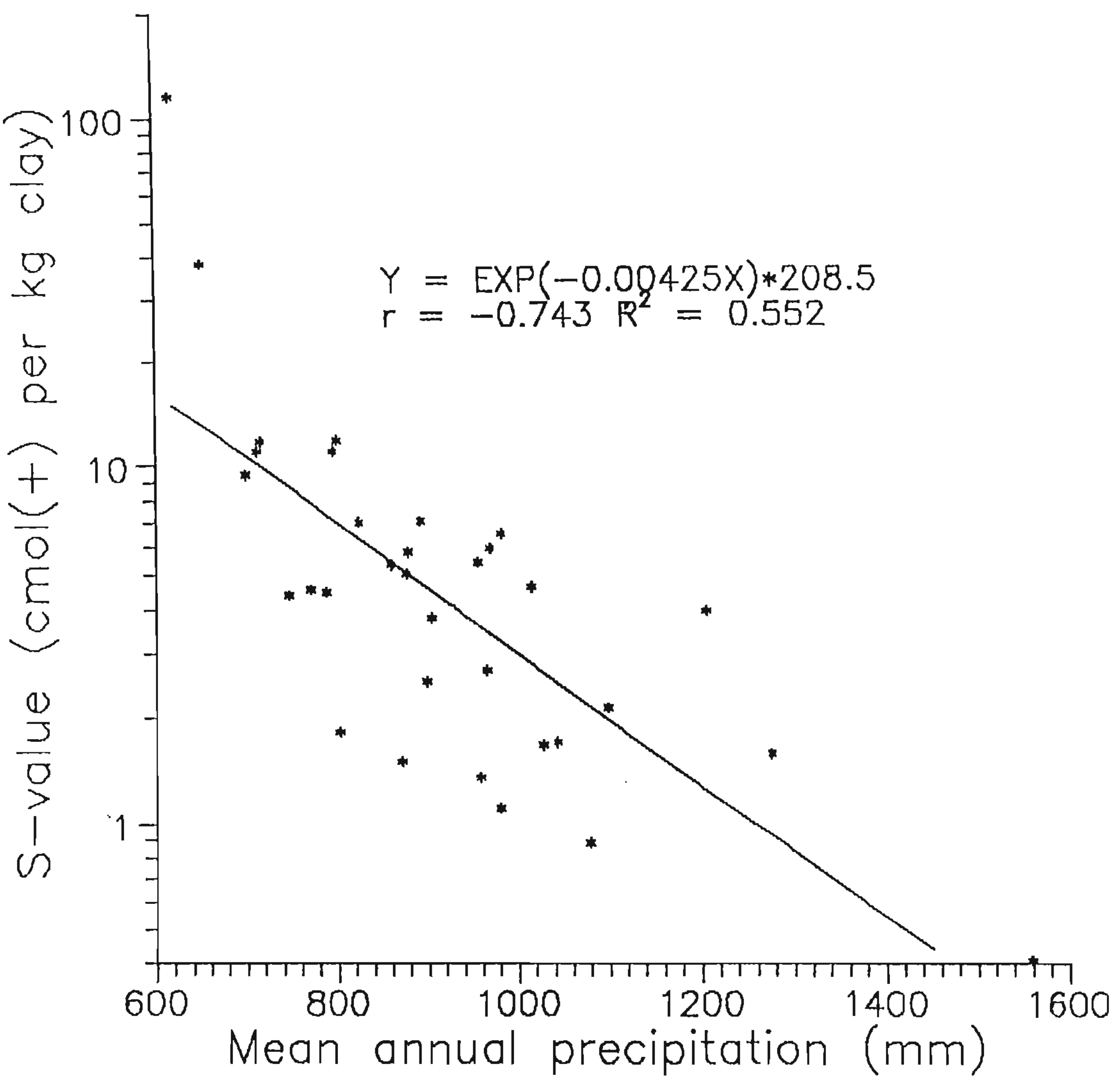

Figure 8. The relationship between MAP and the S-value per unit mass of clay for B1 samples from 33 sites in the Natal midlands.

If the relationship is used to predict MAP (as the dependent variable) from the S-value per unit mass of clay (as the independent variable), then the regression becomes:

Linear model: Y = a + blnX

Dependent variable - Mean annual precipitation (MAP)

Independent variable - Log_e (S-value per unit mass of clay)

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	1103.18	37.903	29.105	<0.0001
Slope	-129.80	21.014	-6.177	<0.0001

Analysis of Variance (ANOVA):

Source	Sum of Squares	Df	Mean Square	F-ratio	Prob.level
Model	637034	1	637034	38.152	0.0000
Error	517618	31	16697		
Total (Corr.)	1154652	32			

Correlation coefficient = -0.7428
Standard error of estimation = 129.22mm
R^2 = 0.5517

This relationship is only marginally improved using mean annual effective rainfall (MAER) as the climatic index ($r=-0.76^{***}$, see Figure 9), and is markedly poorer using mean annual drainage from the B1 horizon (MAD [B1 horizon])($r=-0.55^{***}$), as modelled by ACRU.

These graphs demonstrate that while there are statistically highly significant relationships (all within $p<0.01$) between $\log_e$(S-value per unit mass of clay) and the climatic indices, the relationships are not strong enough to permit any useful estimations of indices of climate from the S-value per unit mass of clay. For example, using the sites in this study, S-value per unit mass of clay values of around 4$\text{cmol}_c\ \text{kg}^{-1}$ were obtained from sites spanning a rainfall range of approximately 750mm to 1200mm per annum (Figure 8).

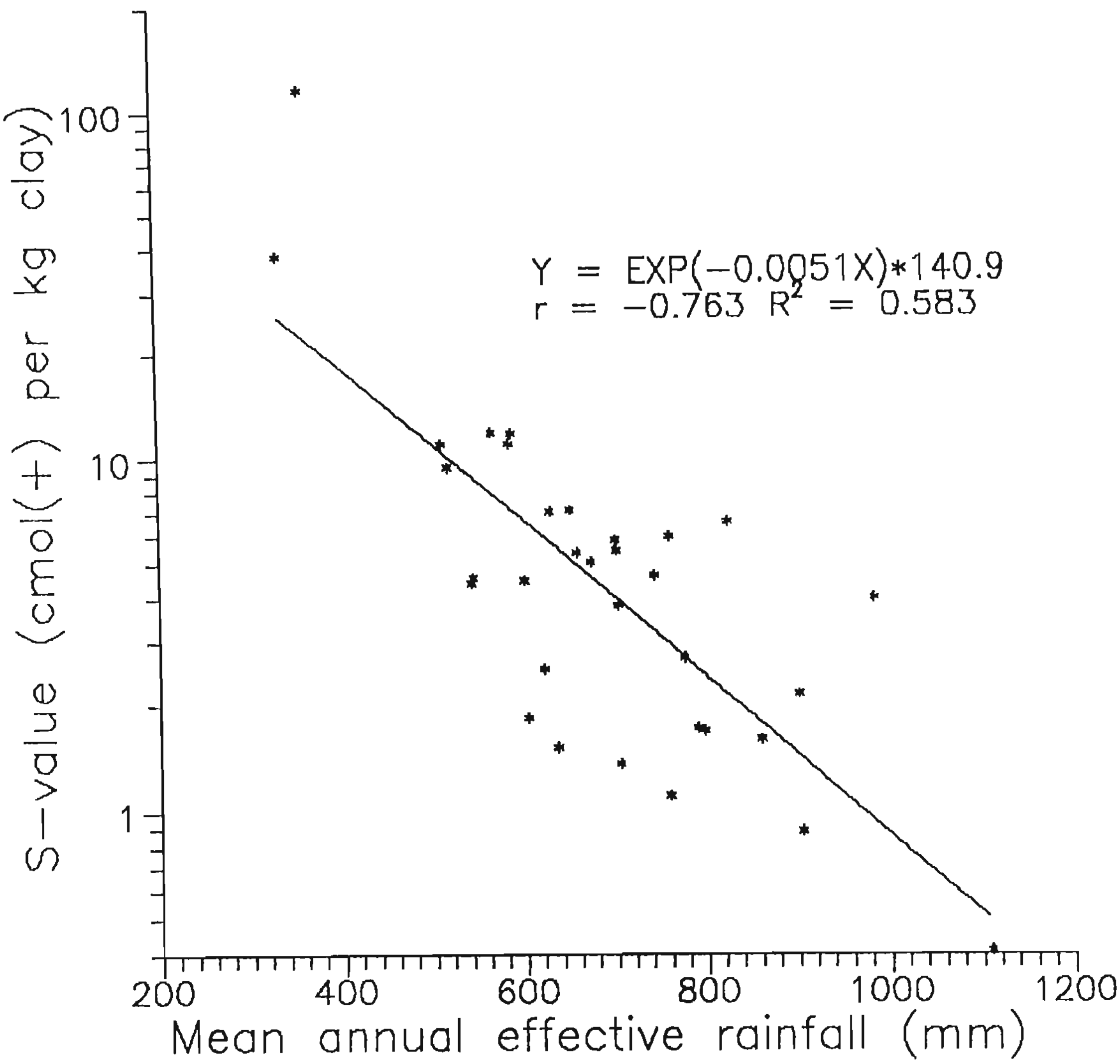

Figure 9. The relationship between MAER and the S-value per unit mass of clay for B1 samples from 33 sites in the Natal midlands.

The common belief that soils formed on base rich parent materials (such as dolerite) give rise to higher S-values than those found in soils derived from base impoverished parent materials (such as sandstone) under similar conditions (Grey *et al.*, 1987) was tested by stratifying the sites according to the lithology of the parent materials from which each soil was presumed to have been derived (Figure 10).

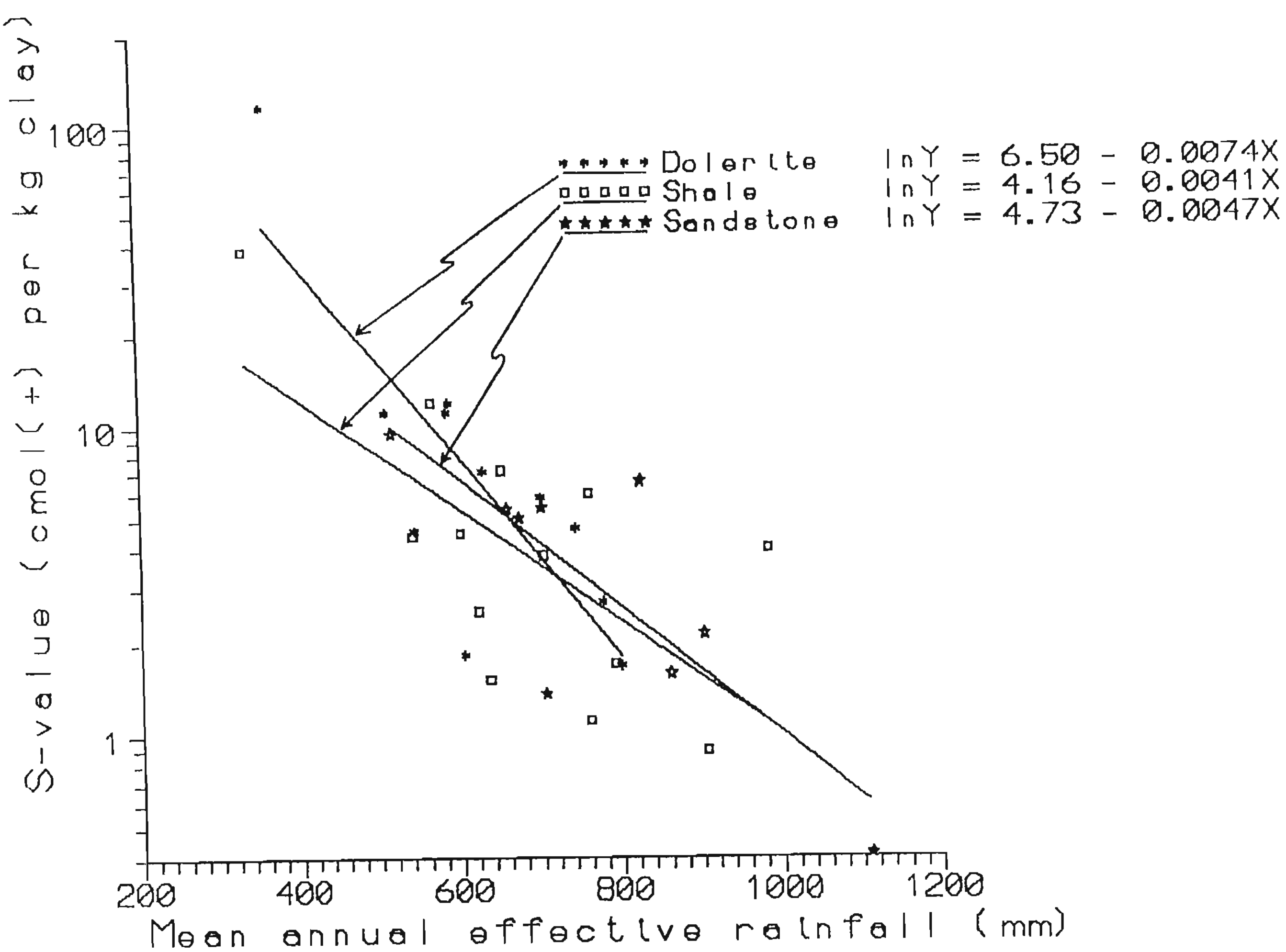

Figure 10. The relationship between MAER and S-value per unit mass of clay for B1 samples from 33 sites in the Natal midlands, stratified according to lithology of the parent material.

The gradient of the dolerite regression line is noticeably steeper than those for shale and sandstone and the dolerite regression line intercept (MAER = 0mm, no weathering) occurs at a higher value than those for the other parent materials. It is recognised that siliceous sedimentary parent materials, such as shale and sandstone, have already passed through at least one cycle of weathering and are considered to supply fewer weatherable minerals (Young, 1976, p.19). Through the use of dummy variables, however, in a forward stepwise variable selection in a multiple regression procedure, it was found that the intercepts and slopes of the regression lines associated with each parent material were not statistically significantly different from each other. The hypothesis that, all soil forming factors other than parent material being equal, soils derived from dolerite have significantly higher S-values than soils formed on their counterparts of a more acidic nature (Grey *et al.,* 1987, p.74), could therefore not be confirmed for this data set. Such differences may only become statistically significant in regions of greater aridity, a conclusion supported by Jenny (1941, p.62). Thus, for the forestry regions of southern Africa to which Grey *et al.* (1987) were referring, this assumption may not be valid.

The factor analyses in section 3.2 indicated that the monovalent cations did not contribute markedly to indices of the degree of leaching. If the S-value per unit mass of clay is recalculated, excluding the monovalent cations, it may be shown that this new index is not only highly related to the original S-value per unit mass of clay ($r = 0.99^{***}$), but also results in an improvement in the relationship with MAER (Figure 11).

This relationship (Figure 11) accounts for 65.1% of the variance in the data set, compared to 55.2% of the variance explained by the corresponding relationship using the original S-value per unit mass of clay, a result which provides additional justification for the exclusion of the monovalent cations from such indices of the degree of leaching, insofar as they are to be used to indicate the effective rainfall of a site.

As a further exercise, the S-value *per se* (rather than the S-value per unit mass of clay) was related to the indices of climate. This index of leaching was proposed by van der Eyk (1965b) but was subsequently superseded by the same index per unit mass of clay in the 1977 classification system (MacVicar *et al.*, 1977) (see section 1.4.). Again, in this exercise the monovalent cations are excluded for the reasons given above, and the relationship shown in Figure 12 was obtained.

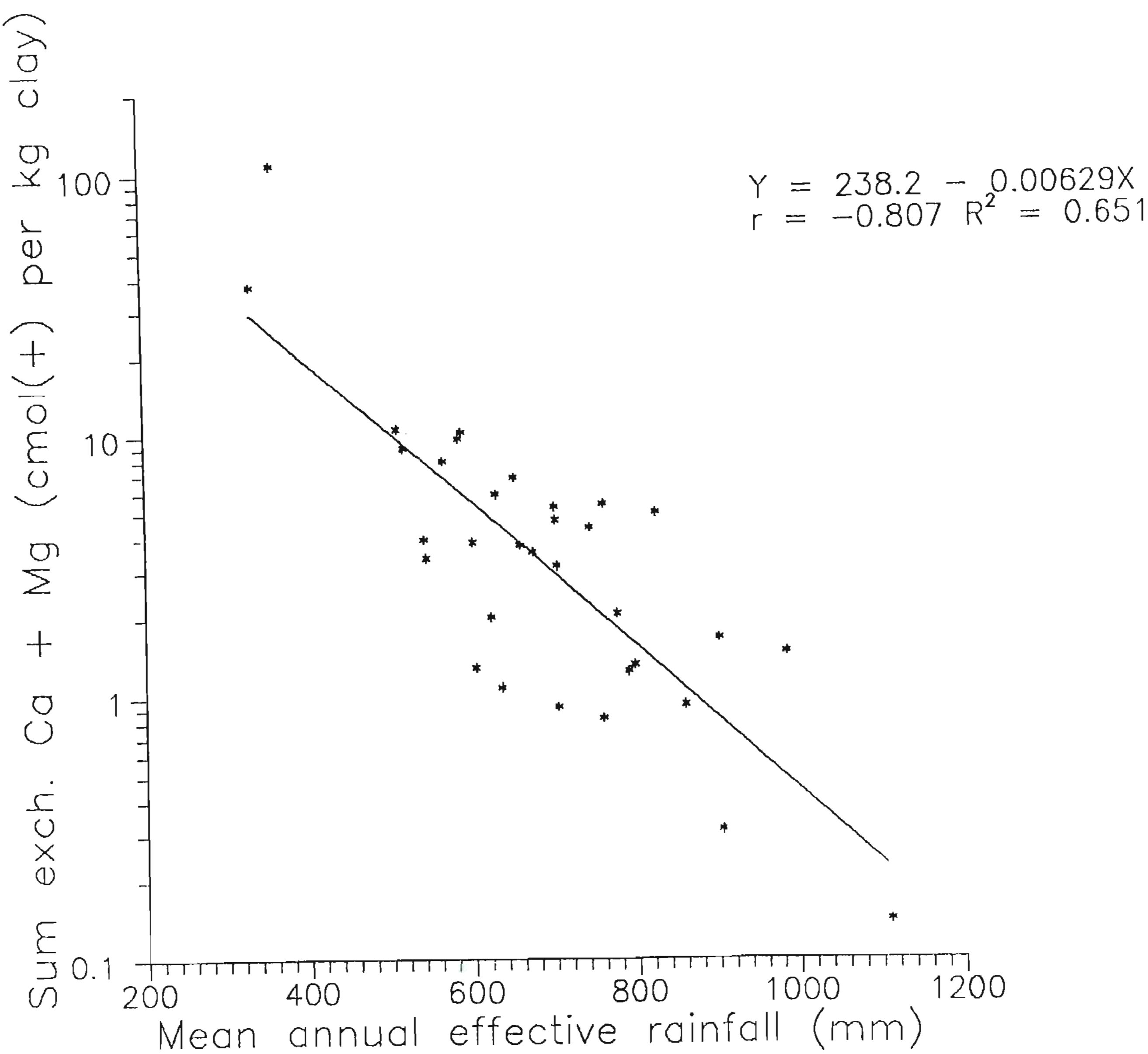

Figure 11. The relationship between MAER and exchangeable Ca^{2+} + Mg^{2+} per unit mass of clay for B1 samples from 33 sites in the Natal midlands.

The re-expression of the index per unit mass of soil provides further improvements in the relationships with the climatic indices, with the relationship now accounting for 73.5% of the variance in MAER. This improvement was unexpected, as the cation exchange sites are expected to be associated predominantly with the clay colloid fraction. It may well be that clay mineralogical differences as well as the contribution of organic matter are sufficiently large to override the effect of clay content *per se* (the clay content of the soil may not be a realistic enough measure of the activity of the clay fraction, or of the exchange characteristics of the soils in general. MacVicar (1965b) also indicates that some intermediate products of weathering such as chlorite, serpentine and sericite, which are not part of the clay-size fraction, nevertheless possess exchange properties).

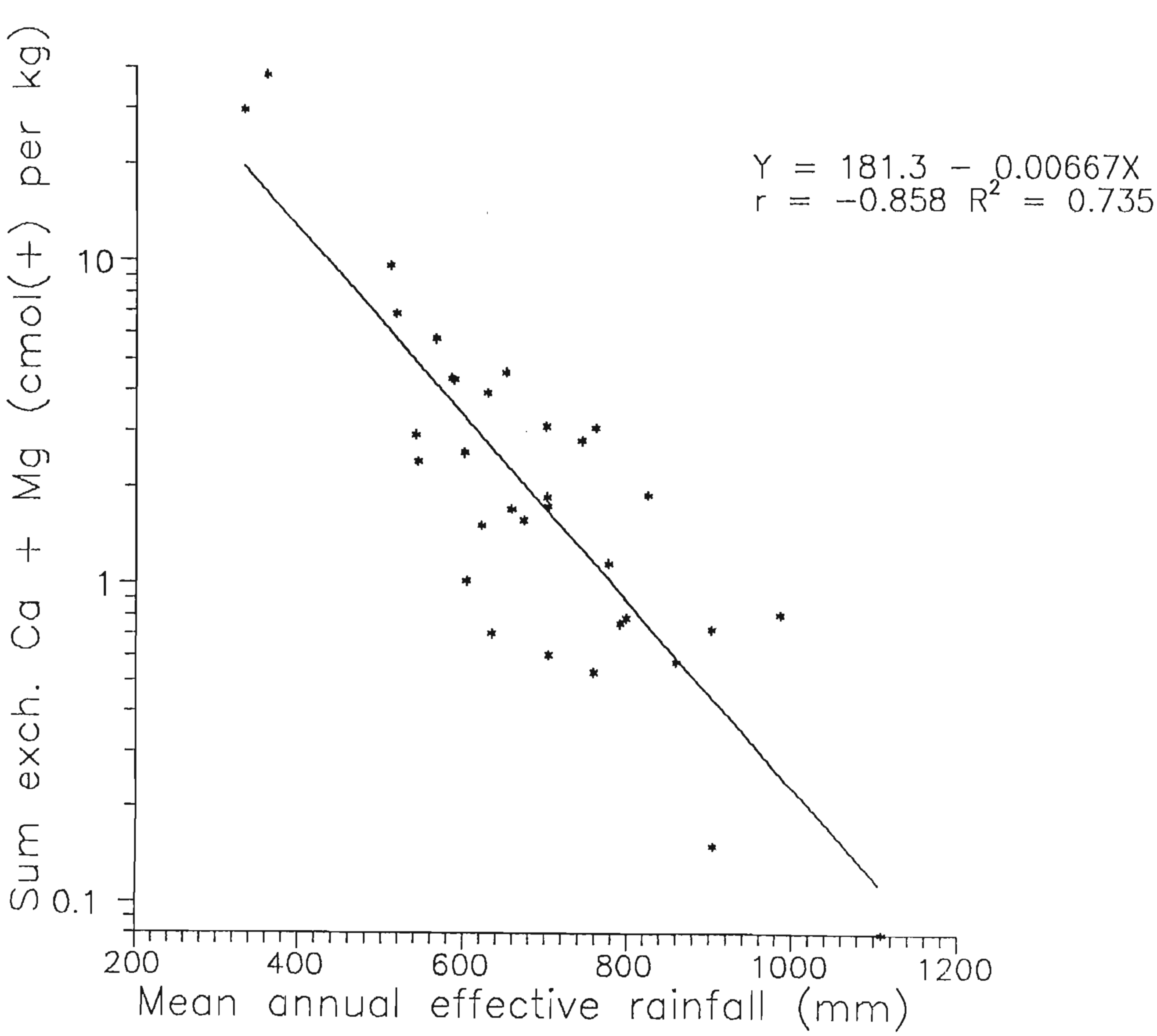

Figure 12. The relationship between MAER and exchangeable Ca^{2+} + Mg^{2+} per unit mass of soil for B1 samples from 33 sites in the Natal midlands.

The specific surface area (SSA) of these soils was also determined, using ethylene glycol monoethyl ether (Carter *et al.*, 1986; see Appendix B), in order to investigate the relationship of this property with clay content and to see if an improvement in the relationships of these soil indices associated with the S-value could be improved by the incorporation of the SSA. Juo (1981) discusses the relative interaction between iron oxides and kaolin for different parent materials and the relative differences in total specific surface area per unit mass of clay for different soils. Juo (1981) states:

> "...it appears probable that it is the surface reactivity of the iron oxides, rather than the total amount present in the soil, that is crucial in influencing the chemical and physical properties of the soil."

Although a significant but weak relationship between clay content and SSA was obtained ($r = 0.39^{*}$, $p<0.05$), the S-value indices were not notably improved when expressed per unit surface area, instead of per unit mass of clay. It would appear that the SSA is not necessarily a better measure of surface reactivity than clay content.

If the indices of climate and the natural logarithm of the S-value per unit mass of clay and its modifications are all correlated and also stratified according to the lithology of the parent materials from which each soil is derived, the following correlation matrices result:

All soils (n=33):

1	MAP	1.00							
2	MAER	0.94***	1.00						
3	MAD [B1 horizon]	0.84***	0.81***	1.00					
4	Clay %	-.22	-.32	-.34	1.00				
5	ln(S-value)	-.79***	-.83***	-.63***	0.12	1.00			
6	ln(S-value/unit clay)	-.74***	-.76***	-.55***	-.10	0.98***	1.00		
7	ln(Ca+Mg)	-.82***	-.86***	-.67***	0.14	0.99***	0.96***	1.00	
8	ln((Ca+Mg)/unit clay)	-.79***	-.81***	-.61***	-.05	0.97***	0.99***	0.98***	1.00
		1	2	3	4	5	6	7	8

Soils derived from shale (n=13):

1	MAP	1.00							
2	MAER	0.98***	1.00						
3	MAD [B1 horizon]	0.92***	0.87***	1.00					
4	Clay %	-.80**	-.86***	-.71**	1.00				
5	ln(S-value)	-.68*	-.73**	-.48	0.63*	1.00			
6	ln(S-value/unit clay)	-.63*	-.68*	-.42	0.55	0.99***	1.00		
7	ln(Ca+Mg)	-.76**	-.81***	-.58*	0.70**	0.98***	0.96***	1.00	
8	ln((Ca+Mg)/unit clay)	-.73**	-.77**	-.54	0.63*	0.98***	0.97***	1.00***	1.00
		1	2	3	4	5	6	7	8

Soils derived from dolerite (n=11):

1	MAP	1.00							
2	MAER	0.95***	1.00						
3	MAD [B1 horizon]	0.88***	0.79**	1.00					
4	Clay %	0.15	0.14	-.02	1.00				
5	ln(S-value)	-.79**	-.86***	-.66*	-.33	1.00			
6	ln(S-value/unit clay)	-.76**	-.81**	-.59	-.53	0.98***	1.00		
7	ln(Ca+Mg)	-.76**	-.83**	-.63*	-.33	1.00***	0.97***	1.00	
8	ln((Ca+Mg)/unit clay)	-.79*	-.79**	-.57	-.52	0.98***	1.00***	0.98***	1.00
		1	2	3	4	5	6	7	8

Soils derived from sandstone (n=9):

1	MAP	1.00							
2	MAER	0.95***	1.00						
3	MAD [B1 horizon]	0.79*	0.73*	1.00					
4	Clay %	0.00	-.20	-.21	1.00				
5	ln(S-value)	-.92***	-.89**	-.77*	0.02	1.00			
6	ln(S-value/unit clay)	-.89**	-.82**	-.70*	-.23	0.97***	1.00		
7	ln(Ca+Mg)	-.93***	-.89**	-.79*	-.02	0.99***	0.97***	1.00	
8	ln((Ca+Mg)/unit clay)	-.91***	-.83**	-.73*	-.21	0.97***	0.99***	0.98***	1.00
		1	2	3	4	5	6	7	8

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

The above correlation matrices allow the following conclusions to be drawn:

i) The S-value and its modifications are all highly related to each other, for all parent materials. There seems to be little justification for the inclusion, or exclusion (apart from analytical convenience), of the monovalent cations when calculating these indices of leaching.

ii) Reasonable correlations (r>0.6) between indices of climate and the S-value or its subsequent modifications hold for all three parent materials.

iii) There are generally no significant correlations between clay content and climatic indices, except for those soils derived from shale. For this sub-set of soils there is a statistically significant negative correlation between clay content and rainfall. This is unexpected and may be fortuitous, as it would be expected that with increasing intensity of climate, and hence leaching and weathering, there would be a tendency for an increasing clay content, as has been observed in other parts of the world (Jenny, 1941, 1980). Most of these other observations, however, have occurred in regions generally more arid than the Natal midlands, and Jenny (1980) also reports that a study on the island of Mauritius showed a decrease in clay content with increasing rainfall for basalt derived soils. It may be that the effect of temperature in the relationship with clay content is dominant over that of rainfall (Jenny, 1936) and in this region there is an inverse relationship between temperature and altitude and a direct relationship between rainfall and altitude. It is possible in the Mauritian study, however, that the inverse relationship between rainfall and clay content is a result of Fe and Al oxide accumulation aggregating and cementing the clay into silt and sand particles, resistant to normal mechanical methods of dispersion in particle size analysis.

A plot of the natural logarithm of the best of the modified S-value indices (exchangeable Ca^{2+} + Mg^{2+} expressed per unit mass of soil) against MAER, with different regression lines for parent material stratification indicates that there is little difference between the regression lines in terms of gradients or intercepts (Figure 13). This was confirmed statistically through the use of dummy variables (stratifying the parent materials) in a forward stepwise multiple regressional search.

4.1.2 Base saturation

Several major soil classifications use base saturation as an index of degree of leaching, as outlined in section 1.4. Young (1976, p.72) reports that base saturation of the subsoil is a good indicator of how intensely a soil is being leached and may be used as a differentiating property indicative of soil genetic conditions. The perceived advantages of using base saturation is that it is a *proportional* index and that it theoretically takes into account to some extent, the base richness of the parent material and the contribution made by organic matter to the cation exchange capacity. As yet, base saturation has not been used formally in South African soil classifications. The reasons for this have been summarised by van der Eyk *et al.* (1969) and are largely concerned

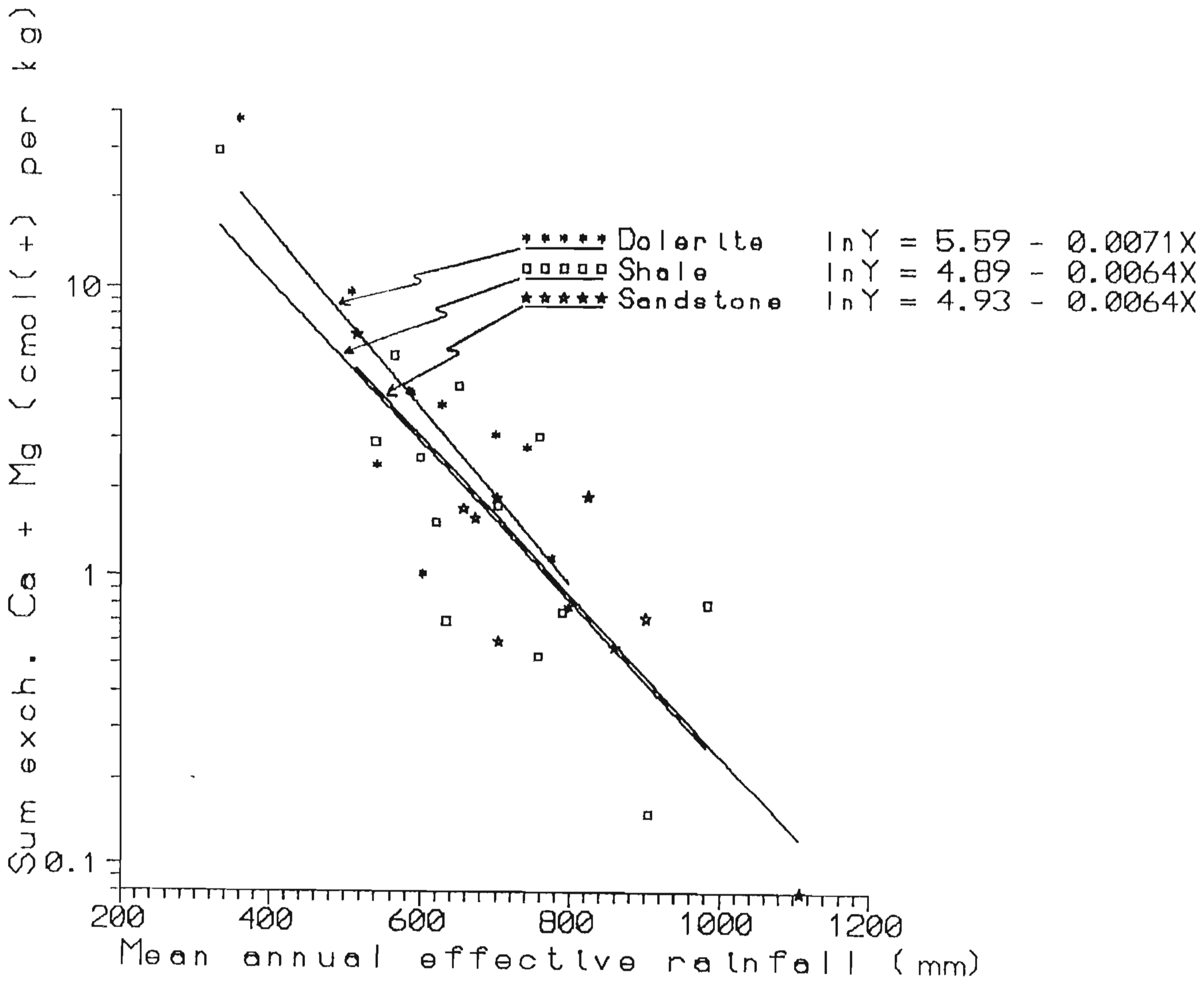

Figure 13. The relationship between MAER and exchangeable Ca^{2+} + Mg^{2+} per unit mass of soil for B1 samples from 33 sites in the Natal midlands, stratified according to lithology of the parent material.

with uncertainty in the determination of cation exchange capacity (CEC) for variable charge soils. The variable charge nature of the soils of the Natal midlands and Tugela basin regions has been investigated in some detail by le Roux and de Villiers (1966). The most recent update of the soil classification for South Africa (Soil Classification Working Group, 1991), in the definition of soil base status, entertains the possibility that base saturation may supplant the S-value per unit mass of clay as an index of the degree of leaching, once sufficient data are available (p.41). If the base saturation is derived from the effective cation exchange capacity (ECEC)[12] (see section 4.2.1), then it is calculated as follows:

$$\text{Base saturation (\%)} = \frac{\text{S-value}}{\text{ECEC}} \times 100$$

Base saturation in general is criticized by Duchaufour (1977, pp.403, 410) as being dependent upon biogeochemical cycles and thus on the present day soil-vegetation equilibrium, very often disturbed by man. Duchaufour (1977, p.410) states:

> "The biogeochemical cycle is related to the present-day climate and vegetation and is independent of weathering, which reflects a slow process, which is much older".

Using ECEC, Juo (1981) recommends that a base saturation of 70% in the diagnostic B horizon should be used as a criterion for the distinguishing between Alfisols and Ultisols in Soil Taxonomy. It is acknowledged that in Ultisols the biogeochemical cycle can raise the base saturation of the surface horizons, which therefore should not be considered. A certain transport of the bases can occur, however, and also raise the base saturation of the B_t horizon abnormally.

For the Natal midlands sites, the relationship between base saturation and the S-value (clay basis) is displayed in Figure 14.

---

[12]Sum of 1M ammonium acetate extractable Ca^{2+}, Mg^{2+}, K^+, Na^+ and 1M KCl extractable acidity determined by titration with 0.001M NaOH, expressed in $cmol_c\ kg^{-1}$.

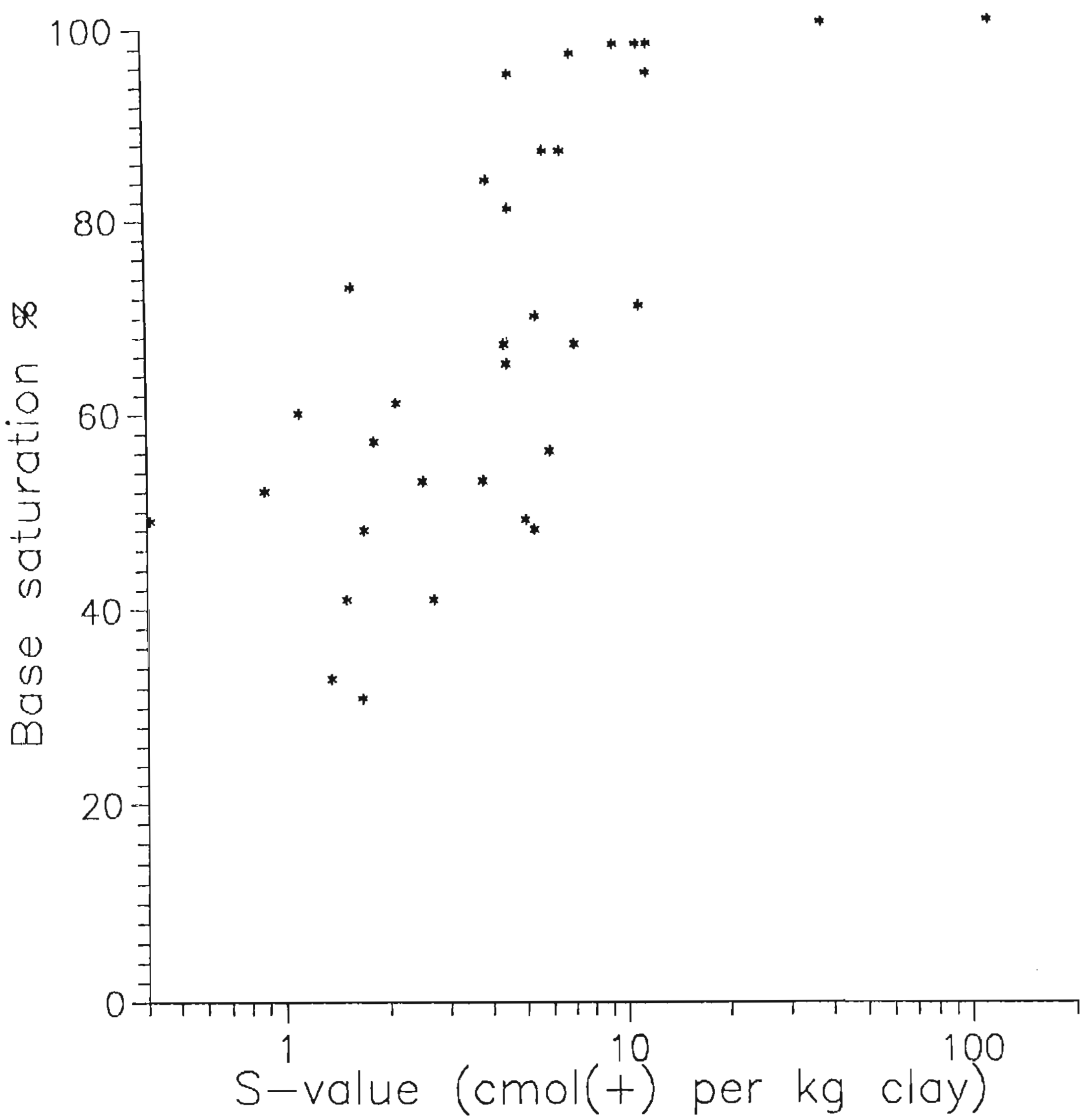

Figure 14. The relationship between base saturation and $\log_e$(S-value per unit mass of clay) for B1 samples from 33 Natal midlands sites.

Lambrechts (1990) has also related base saturation, calculated both on ECEC determined by summation of basic and acidic cations and on CEC determined by neutral ammonium acetate displacement, with the S-value expressed per unit mass of clay and has found broad relationships between them. The use of these relationships, however, for the estimation of either base saturation from the S-value per unit mass of clay, or *vise versa*, is of limited practical use given the large standard errors of estimation associated with the equations given by Lambrechts (1990).

For a set of soils sampled along a transect with a moisture gradient in California, Jenny *et al.* (1968) obtained a highly positive linear correlation between percent acid saturation (equivalent to 100 - base saturation) and MAP, with MAP accounting for 80.9 % of the total variance in percent acid saturation. Jenny (1980, p.323) also reports a strong linear relationship (r = 0.913) between acid saturation and MAP for the A horizons of soils formed from basic igneous rocks in California.

Kohnke *et al.* (1968) have obtained negative linear relationships between base saturation and a "biofactor" (a slight modification of Lang's *Regenfaktor* (1915), see section 1.3.4.1) for A horizon soils from around the world. Kohnke *et al.* also noted the influence of the parent material on this relationship, with soils derived from basic parent materials having higher base saturations than soils derived from more acidic parent materials, under equivalent conditions. A plot of base saturation against MAER for the Natal midlands data set is displayed in Figure 15.

If the monovalent cations are excluded from the calculation of base saturation, a modified index, which may be termed for the sake of convenience the dibasic cation saturation, is formed:

$$\text{Dibasic cation saturation (\%)} = \frac{\text{Sum exch.(Ca + Mg) x 100}}{\text{Sum exch.(Ca + Mg + acidity)}}$$

The dibasic cation saturation index, while still correlating highly with base saturation ($r=0.894^{***}$), demonstrates a noticeable skewness to the regression line with base saturation (Figure 16), indicating that, in general for this set of soils, the lower the base saturation the greater the relative proportion of bases extracted which are monovalent.

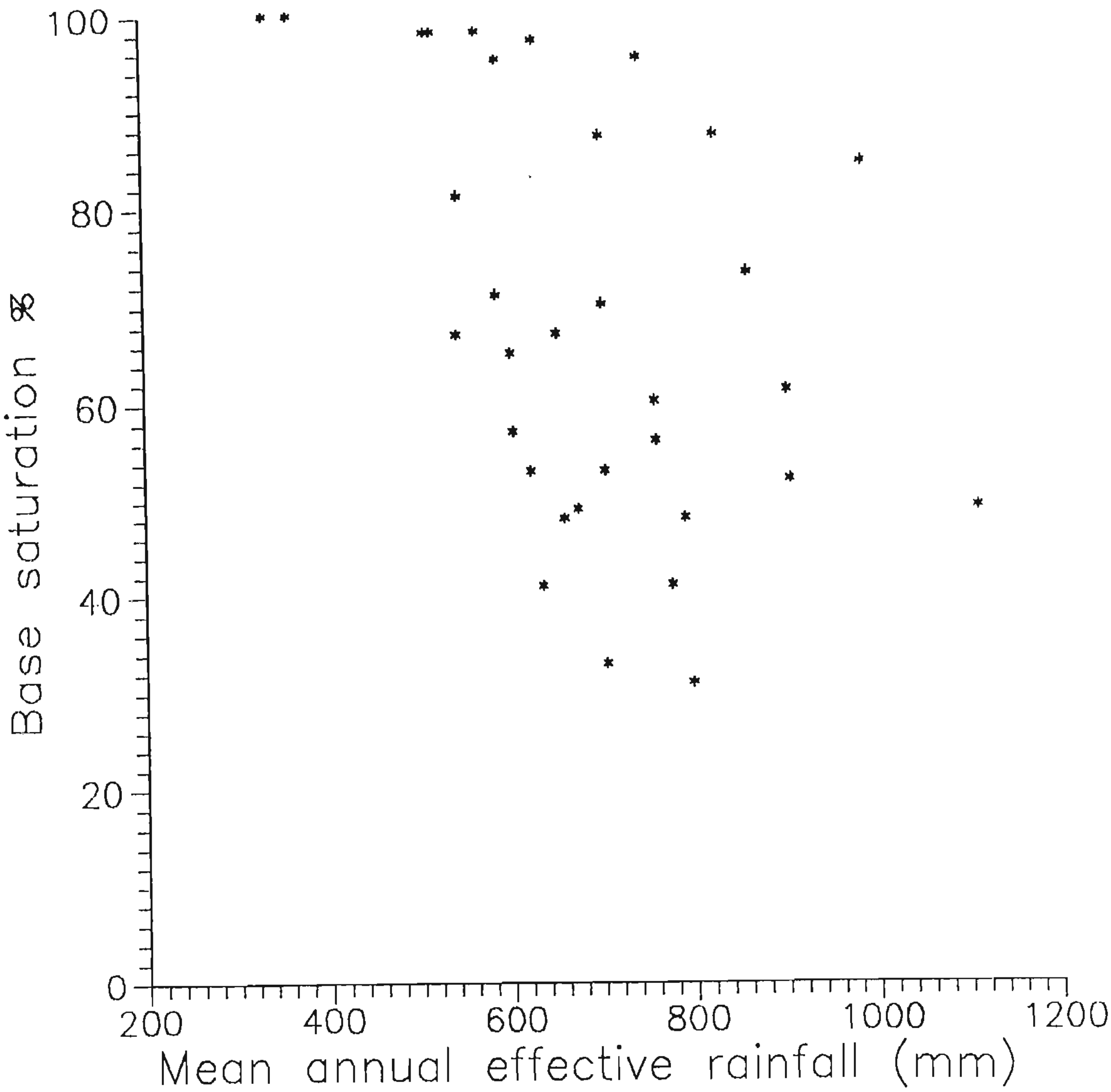

Figure 15. The relationship between MAER and base saturation for B1 samples from 33 sites in the Natal midlands.

Evidence of the sigmoidal curve expected in theory with climatic indices becomes clearer using the dibasic cation saturation index. A visual inspection, however, shows that the relationship is still not good enough to enable the estimation of MAER, or even to challenge the currently used S-value expressed per unit mass of clay, and does not warrant the mathematical fitting of a sigmoidal curve (compare Figure 15 with Figure 17).

Problems occur, however, with the determination of base saturation, for very highly weathered soils, such as the Magwa sampled at Qudeni. The base saturation of the B1 of this soil (49%) is surprisingly high for such a highly leached and highly weathered soil, yet on examination, the ECEC is very low (0.49cmol$_c$ kg^{-1} soil) and the bulk (67%) of the basic cations on the exchange complex is made up of monovalent cations. The soil is likely to be very near its point of zero charge (PZC), indicating a high degree of weathering (Herbillon, 1981), with little or no clay migration down the profile (see Qudeni analytical data, Appendix A).

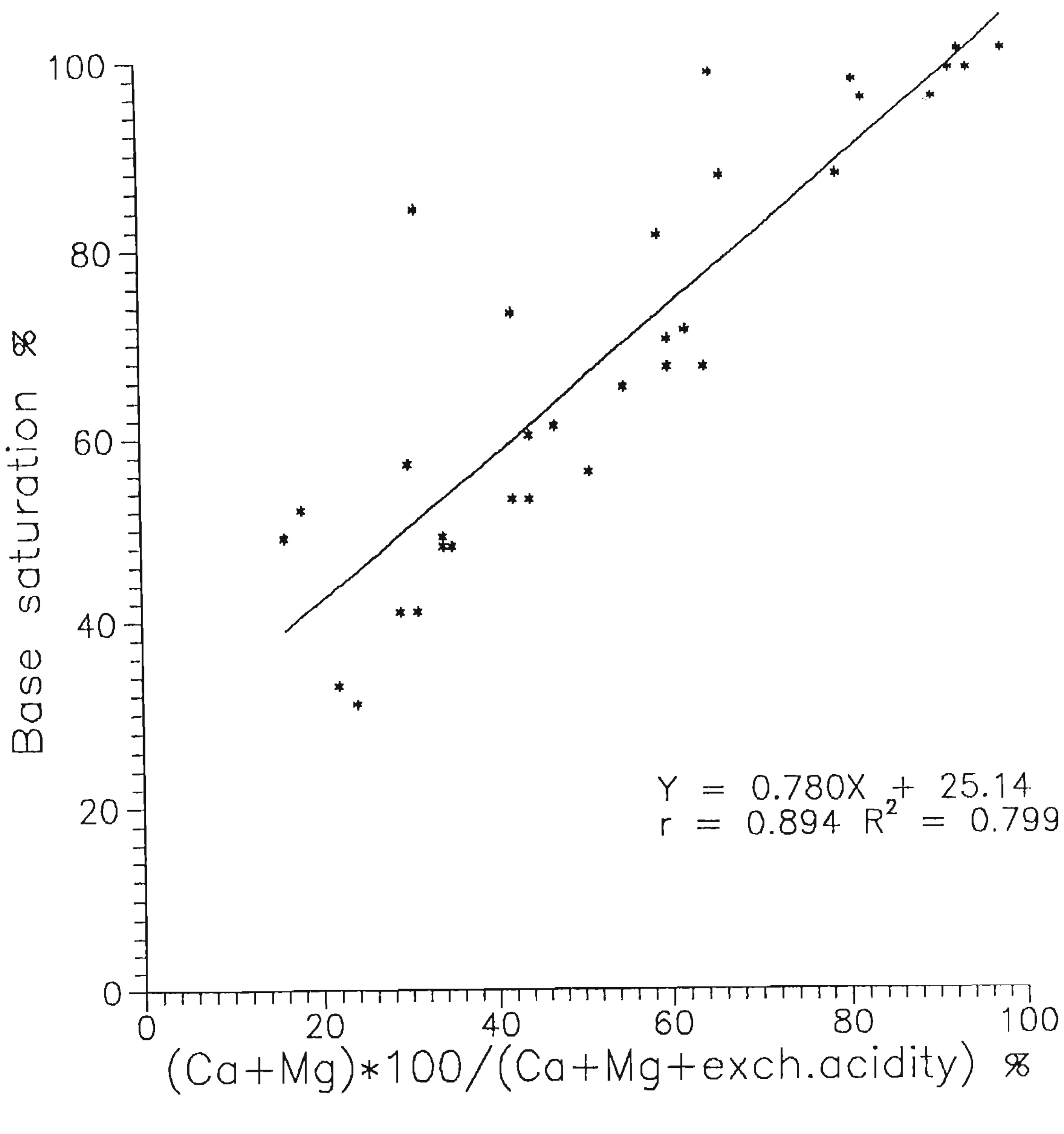

Figure 16. Base saturation versus dibasic cation saturation index for 33 B1 soils sampled at sites in the Natal midlands.

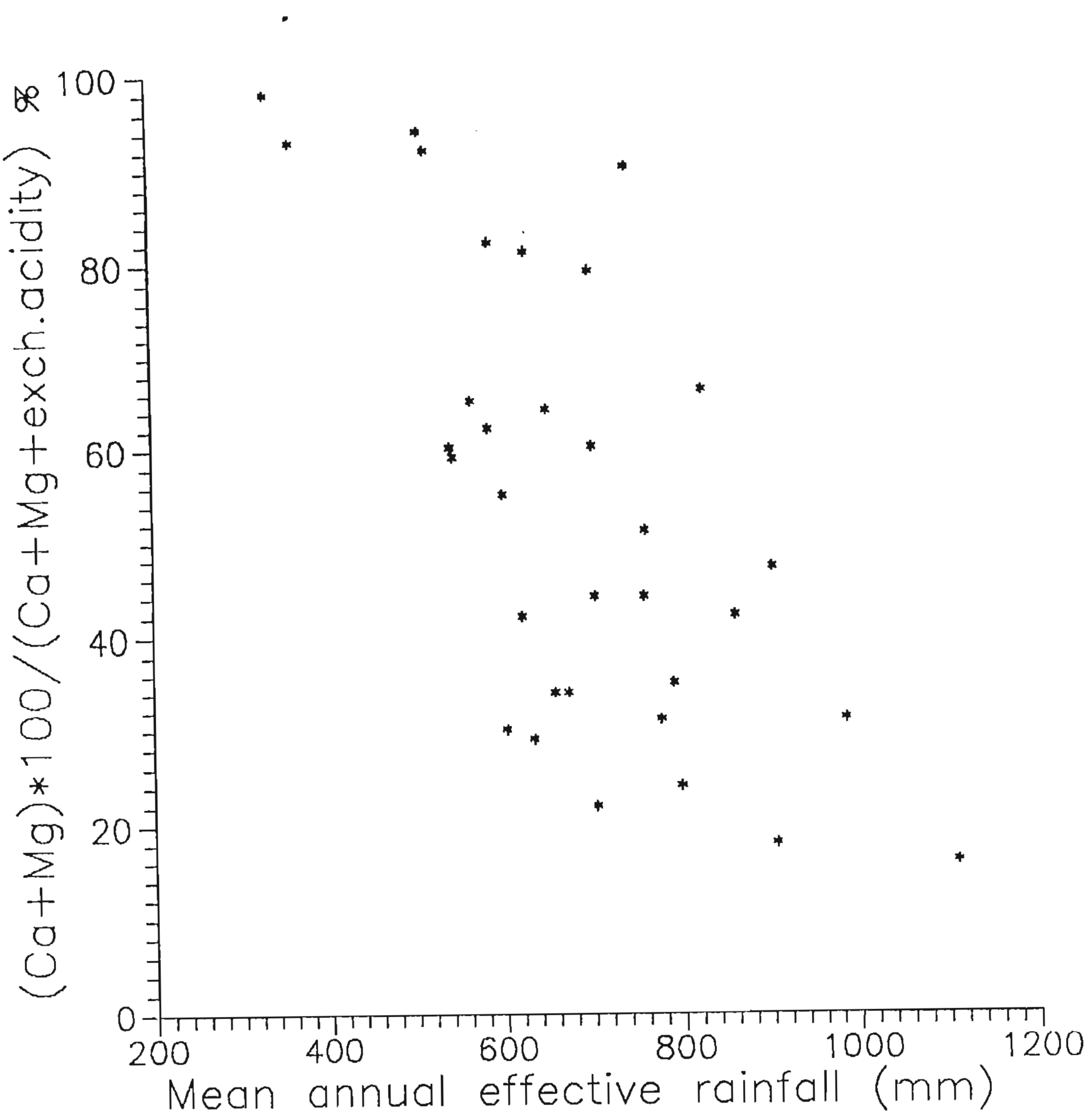

Figure 17. The relationship between MAER and dibasic cation saturation % for B1 samples from 33 sites in the Natal midlands.

Furthermore, for such low ECEC soils, the amounts of exchangeable bases and acidity are approaching the levels of analytical error associated with these types of analysis, and thus the relative margin for error in such determinations could be considerable. Eswaran and Tavernier (1980, p.436) consider base saturation to be:

> "...less meaningful in materials with a very low cation exchange capacity, where a small increase in bases can shift the base saturation markedly".

They also consider the occurrence of eutric great groups (high base saturation) with low CEC in Soil Taxonomy (Soil Survey Staff, 1975), to be a genetic paradox, and suggest that base saturation is a secondary feature to the strong weathering necessary for the production of a low CEC soil, with the bases being supplied from external sources.

Van Wambeke (1989) also reports determinate errors of up to 30% (absolute) in the base saturation, using high-precision analytical methods in samples having a CEC of 10cmol$_c$ kg^{-1} soil and a 50% base saturation. Obviously, the use of such an uncertain index is of limited worth for soil classification, let alone its use in the estimation of climatic indices. More emphatically, van Wambeke (1989) quotes van Reeuwijk (1984)[13], who compares the separation of certain soils using the criterion of base saturation, to playing dice!

There are no indications of any significant differences in the relationships brought about by stratifying the sites according to the lithology of the parent material. Correlation matrices reflecting the relationships between climatic indices and the two cation saturation indices are presented (p.116) for the 33 sites, including stratification according to the lithology of the parent material.

[13]**Van Reeuwijk, L.P.**, 1984. Laboratory methods and data exchange program for soil characterization. A report on the pilot round. Part II: Exchangeable bases, base saturation and pH. Technical paper no.8, pp.28, ISRIC, Wageningen, The Netherlands. Quoted by van Wambeke (1989).

Correlation matrices

All soils (n=33):

1	MAP	1.00				
2	MAER	0.94***	1.00			
3	MAD [B1 horizon]	0.84***	0.81***	1.00		
4	base saturation %	-.43*	-.46**	-.39*	1.00	
5	dibasic cation sat%	-.63***	-.66***	-.56***	0.89***	1.00
		1	2	3	4	5

Shale (n=13):

1	MAP	1.00				
2	MAER	0.98***	1.00			
3	MAD [B1 horizon]	0.92***	0.87***	1.00		
4	base saturation %	-.35	-.40	-.17	1.00	
5	dibasic cation sat%	-.80**	-.84***	-.62*	0.71**	1.00
		1	2	3	4	5

Dolerite (n=11):

1	MAP	1.00				
2	MAER	0.95***	1.00			
3	MAD [B1 horizon]	0.88***	0.79**	1.00		
4	base saturation %	-.60	-.61*	-.59	1.00	
5	dibasic cation sat%	-.50	-.53	-.47	0.96***	1.00
		1	2	3	4	5

Sandstone (n=9):

1	MAP	1.00				
2	MAER	0.95***	1.00			
3	MAD [B1 horizon]	0.79*	0.73*	1.00		
4	base saturation %	-.27	-.25	-.46	1.00	
5	dibasic cation sat%	-.59	-.54	-.64	0.92***	1.00
		1	2	3	4	5

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

4.1.3 Exchangeable Ca and Mg and the Ca:Mg ratio

It has been surmised that the ratio of exchangeable Ca^{2+} to exchangeable Mg^{2+} may be an index of the degree of leaching. According to the lyotropic series, based on the radius of the hydrated cation, the premise is that Mg^{2+} will be differentially lost relative to Ca^{2+} under conditions conducive to leaching (Talibudeen, 1981, p.162). Thus a high Ca:Mg ratio should be indicative of a high leaching regime. There appears to be uncertainty, however, with regard to the relative mobility of Ca^{2+} to Mg^{2+} in the weathering zone, as evidenced by the variety of relative mobility schemes presented by several authors and listed by Chesworth (1973). Buol *et al.* (1989, p.86) have inferred that the ratio of exchangeable Ca^{2+} to Mg^{2+} is an indicator of relative weathering and degree of development, but report that in humid and subhumid regions, exchangeable Mg^{2+} *increases* relative to Ca^{2+} with increasing soil age and degree of development. Bruce *et al.* (1989b) have also found that low ratios of Ca:Mg for well-weathered acid Queensland soils are common. A possible reason for this discrepancy with the expectations of the lyotropic series of Talibudeen is given by Wild (1988), who indicates that under acid conditions the ratio of exchangeable Ca^{2+} to exchangeable Mg^{2+} narrows due to the slow release of Mg^{2+} from silicates.

For the 33 Natal midlands soils, the concentrations of B1 horizon exchangeable Ca^{2+} and Mg^{2+} and their ratio were correlated with the indices of climate (MAP, MAER, and MAD [B1 horizon]). The sites were again stratified according to the lithology of the parent material from which the soil was derived, on the hypothesis that each parent material is intrinsically different in their Ca and Mg content, as this was noted from analytical data for rocks assumed to be representative of the parent materials from which the soils were formed[14].

Mean Ca and Mg contents of parent materials:

	CaO %	MgO %	Ca (Molecular equivalents)	Mg (Molecular equivalents)	Ca/Mg
Dolerite	10.47	6.23	0.1867	0.1546	1.21
Sandstone	1.20	1.07	0.0214	0.0265	0.81
Shale	0.49	1.42	0.0087	0.0352	0.25

High variance was noted for the sandstone figures.

[14]"Analyses of rocks, minerals and ores", Geological Survey, Pretoria, 1964.

Correlation matrices:

All soils (n=33):

		1	2	3	4	5	6
1	MAP	1.00					
2	MAER	0.94^{***}	1.00				
3	MAD [B1 horizon]	0.84^{***}	0.81^{***}	1.00			
4	ln(exch.Ca)	$-.80^{***}$	$-.80^{***}$	$-.63^{***}$	1.00		
5	ln(exch.Mg)	$-.70^{***}$	$-.73^{***}$	$-.60^{***}$	0.76^{***}	1.00	
6	Ca/Mg	0.04	0.11	0.08	0.14	$-.40^{*}$	1.00

Shale derived soils (n=13):

		1	2	3	4	5	6
1	MAP	1.00					
2	MAER	0.98^{***}	1.00				
3	MAD [B1 horizon]	0.82^{***}	0.87^{***}	1.00			
4	ln(exch.Ca)	$-.70^{**}$	$-.74^{**}$	-.51	1.00		
5	ln(exch.Mg)	$-.79^{**}$	$-.84^{***}$	$-.62^{*}$	0.93^{***}	1.00	
6	Ca/Mg	0.28	0.34	0.29	0.02	-.34	1.00

Dolerite derived soils (n=11):

		1	2	3	4	5	6
1	MAP	1.00					
2	MAER	0.95^{***}	1.00				
3	MAD [B1 horizon]	0.88^{***}	0.79^{**}	1.00			
4	ln(exch.Ca)	-.57	$-.65^{*}$	-.47	1.00		
5	ln(exch.Mg)	-.43	-.43	-.57	0.48	1.00	
6	Ca/Mg	0.21	0.20	0.27	0.27	-.49	1.00

Sandstone derived soils (n=9):

		1	2	3	4	5	6
1	MAP	1.00					
2	MAER	0.95^{***}	1.00				
3	MAD [B1 horizon]	0.79^{*}	0.73^{*}	1.00			
4	ln(exch.Ca)	$-.95^{***}$	$-.89^{**}$	$-.82^{**}$	1.00		
5	ln(exch.Mg)	$-.73^{*}$	$-.73^{*}$	-.60	0.76^{*}	1.00	
6	Ca/Mg	-.27	-.20	-.30	0.25	-.42	1.00

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

While statistically highly significant relationships between the concentrations of the individual dibasic cations and climatic indices are observed for all soils, as would be expected from the results of section 4.1.1, no statistically significant relationships between the Ca:Mg ratio and indices of climate were noted. Stratifying the soils according to the parent material from which they were derived did not result in any improvement in this regard.

4.1.4 Soil acidity

That pH declines with increasing climatic intensity and that exchangeable acidity increases with increased leaching and weathering in humid regions, has been well-established (Buol *et al.*, 1989, pp.86-89) and many trends of this nature have been observed, such as that shown by Prescott (1931). Quantitatively, a highly significant negative correlation has been obtained by Kohnke *et al.* (1968) between pH (unspecified method of determination) and a "biofactor" (a modification of Lang's *Regenfaktor* (1915); see section 1.3.4.1) with a correlation coefficient of -0.65, for A horizon soils from around the world. For the Natal midlands sites, the following correlation matrices, stratified according to parent material, have been constructed:

All soils (n=33):

1	MAP	1.00						
2	MAER	0.94***	1.00					
3	MAD [B1 horizon]	0.84***	0.81***	1.00				
4	pH (1M KCl)	-.08	-.20	-.12	1.00			
5	pH (0.01M $CaCl_2$)	-.26	-.38*	-.27	0.93***	1.00		
6	pH (H_2O)	-.45**	-.52**	-.45**	0.49**	0.53**	1.00	
7	ln(exch. acidity)	0.05	0.13	0.10	-.80***	-.84***	-.48**	1.00
		1	2	3	4	5	6	

Shale derived soils (n=13):

1	MAP	1.00						
2	MAER	0.98***	1.00					
3	MAD [B1 horizon]	0.92***	0.87***	1.00				
4	pH (1M KCl)	-.18	-.22	-.11	1.00			
5	pH (0.01M $CaCl_2$)	-.40	-.47	-.29	0.88***	1.00		
6	pH (H_2O)	-.45	-.51	-.32	0.32	0.25	1.00	
7	ln(exch. acidity)	0.11	0.19	-.03	-.89***	-.80***	-.41	1.00
		1	2	3	4	5	6	

Dolerite derived soils (n=11):

1	MAP	1.00						
2	MAER	0.95***	1.00					
3	MAD [B1 horizon]	0.88***	0.79**	1.00				
4	pH (1M KCl)	-.40	-.55	-.26	1.00			
5	pH (0.01M $CaCl_2$)	-.48	-.60	-.36	0.97***	1.00		
6	pH (H_2O)	-.76**	-.87**	-.57	0.64*	0.69*	1.00	
7	ln(exch. acidity)	0.38	0.42	0.41	-.69*	-.82**	-.53	1.00
		1	2	3	4	5	6	

Sandstone derived soils (n=9):

1	MAP	1.00						
2	MAER	0.95***	1.00					
3	MAD [B1 horizon]	0.79*	0.73*	1.00				
4	pH (1M KCl)	0.37	0.28	0.01	1.00			
5	pH (0.01M $CaCl_2$)	0.17	0.15	-.13	0.96***	1.00		
6	pH (H_2O)	-.21	-.04	-.50	0.39	0.59	1.00	
7	ln(exch. acidity)	-.34	-.31	0.02	-.97***	-.98***	-.58	1.00
		1	2	3	4	5	6	

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

In general, weak negative linear relationships between pH and rainfall were observed for all soils. Plots of the respective pHs', however, revealed evidence of statistically significant quadratic relationships between pH measured in all three electrolytes, with MAER. As an example, the relationship of pH (KCl) with MAER is displayed in Figure 18.

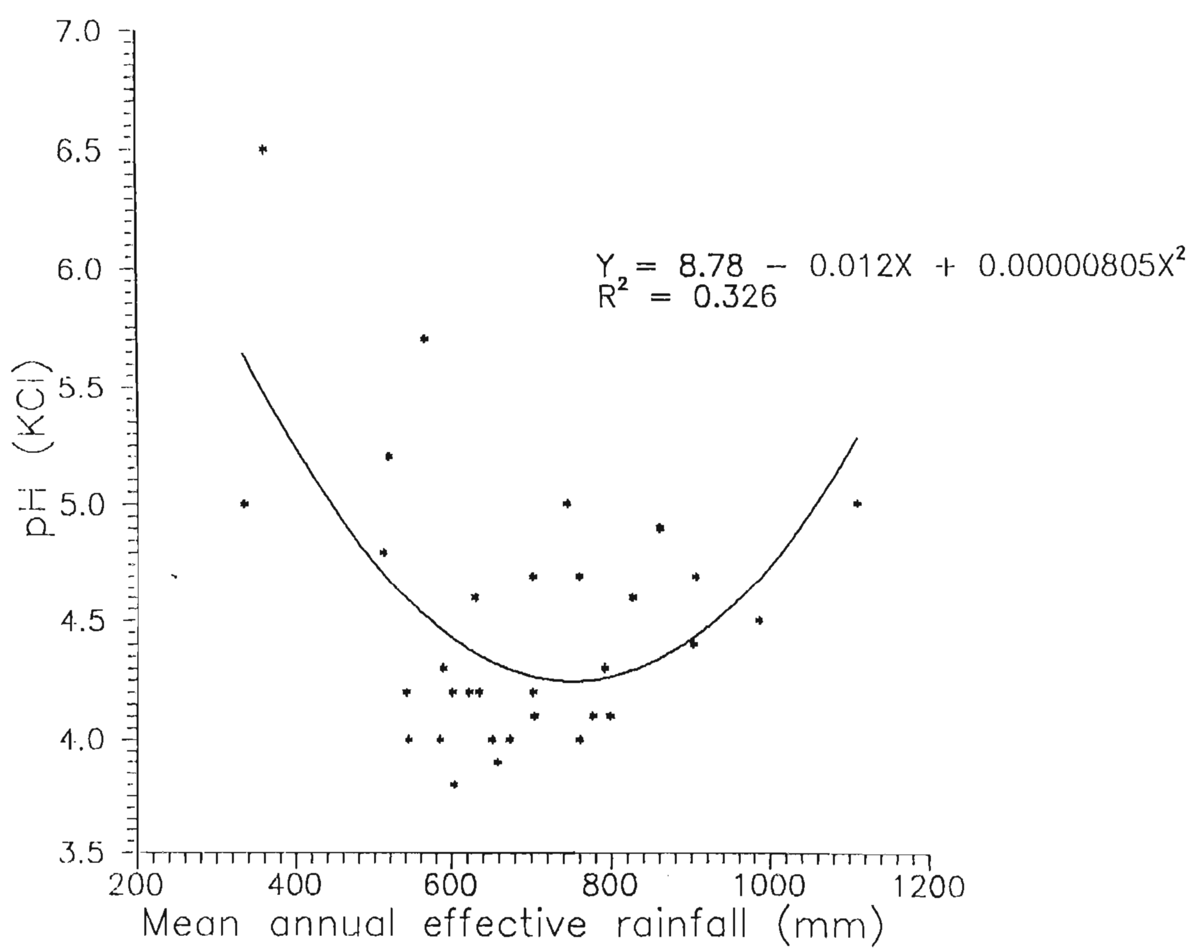

Figure 18. The relationship between MAER and pH (1M KCl) for B1 samples from 33 sites in the Natal midlands.

When the sites are stratified according to the lithology of the parent material, only those soils derived from dolerite retain a statistically significant relationship between pH (and only in this case, pH determined in deionized water) and MAER. This is probably due to the basic nature of dolerite, which will show a more ready response to weathering and leaching in terms of the lowering of pH, whereas shale and especially sandstone are relatively acidic parent materials to begin with, and, under equivalent conditions of leaching and weathering will, not show as marked a decline in pH as doleritic soils.

Quadratic relationships between pH and intensity of climate for highly weathered soils are not unexpected. This is probably due to the change from kaolinite-dominated soils to soils having increasing amounts of gibbsite. The point of zero charge values for pure quartz and kaolinite are below pH 3, whereas the point of zero charge for gibbsite and other hydrous oxide minerals are closer to pH 7 (Juo, 1981, p.56).

No significant relationships between exchangeable acidity and climatic indices were obtained (see correlation matrices pp.119-120), although again, the doleritic soils did display the most pronounced (although not statistically significant) relationships with this soil property.

4.2 Indices of weathering

In contrast to the soil properties examined in the previous section (4.1) which may be best considered as indices of leaching, this section examines other properties which conceptually may be more closely linked to mineralogy and therefore may be taken as indices of weathering.

4.2.1 ECEC

The ability of a soil to adsorb and to reversibly exchange cations has importance for the study of soil fertility as well as for the study of pedogenesis (Buol *et al.*, 1989, p.84). The cation exchange capacity (CEC) of a soil may be regarded as a measure of the extent to which a soil has undergone weathering and is consequently used extensively in several soil classifications (see section 1.4). The CEC of the clay fraction is reported to give an indication of the nature of the clay mineral present (Young, 1976, p.95). A general observation for mature soils, however, is that the clay mineral suite formed in a soil and the composition of the exchange complex, is mainly a reflection of leaching intensity (Dan and Singer, 1973). Thus CEC, while viewed predominantly as an index of the degree of weathering, is also seen as an index of the degree of leaching.

Unfortunately there are a variety of methods for determining the CEC of a soil and not all methods yield results which are strictly comparable. Most of the analytical methods developed for the determination of CEC were generated in the temperate regions, where soils with little pH dependent-, and thus variable-, charge are found. Soils of humid and sub-humid regions, however, are often dominated by variable-charge clays. Several measures of CEC have also been employed in soil classifications for soil series differentiation (see section 1.4 and section 2.4.2). For example, Soil Taxonomy (Soil Survey Staff, 1975) makes use of the sum of cations and exchangeable acidity at pH 8.2 and for these soils of the humid regions, unrealistically high values for exchangeable acidity are obtained by this method. The FAO/UNESCO soil classification (FAO, 1974) determines CEC at pH 7 by neutral 1M ammonium acetate displacement of the exchange complex, but again this invariably results in unacceptably high CEC values for variable-charge soils (Juo *et al.*, 1976; Juo, 1981).

In an attempt to surmount the problem for variable-charge soils, analytical methods have been developed to determine CEC at a pH which better reflects that of the field soil (field-effective CEC). In this regard, an alternative method of CEC estimation has been developed, being the so-called effective cation exchange capacity (ECEC) of a soil, as advocated by the USDA Soil Survey Staff (1975), Juo *et al.* (1976) and Juo (1981). ECEC has been defined by Juo *et al.* (1976) as being the sum of the neutral 1M ammonium acetate exchangeable basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and unbuffered 1M potassium chloride extractable acidity (Al^{3+} and H^+). This index provides a more realistic estimation of CEC under field conditions for variable-charge soils than the classical (and for these soils, inappropriate) methods of CEC determination at a fixed pH of 7 or greater (Juo, 1981). Another major advantage in the use of ECEC for acid soils is that under acid conditions, the contribution to the ECEC by organic matter is relatively low (Buol *et al.*, 1989, p.86).

Expressing CEC in terms of the clay proportion of the soil sample, results in a property referred to as the *apparent CEC* of the soil, or the CEC per unit mass of clay. This apparent CEC is also regarded as an indication of the dominant clay mineral present in a soil, but assumes that all positive charge is held on the clay fraction and that organic matter does not contribute to such charge (Buol *et al.*, 1989, pp.87-88). Duchaufour (1977, p.403) considers apparent CEC to be a more valid criterion for classification than base saturation. It is known, however, that for instance, kaolinite possesses a silt-sized fraction that will contribute to CEC (Young, 1976, p.95). This will therefore be an over-simplification, since most of the soils encountered in this study can be considered to be kaolinite dominated, with ECEC values, per unit mass of clay, of less that $15cmol_c\ kg^{-1}$ clay.

Although the effective CEC (ECEC) is an estimate of CEC specifically developed for the measuring of field-effective CEC for the variable-charge soils commonly encountered in humid or sub-humid regions, it has not yet been entertained by the South African soil classification (Soil Classification Working Group, 1991). Nevertheless, for the purposes of this study this measure of CEC (being ECEC) has been utilized.

Several other researchers have related measures of CEC to climatic indices. Comparative work, however, is not always straightforward since, as discussed previously, there are many methods for determining and reporting measures of CEC.

Jenny and Leonard (1934) obtained a *positive* logarithmic relationship between what they termed the saturation capacity [CEC] and mean annual rainfall, with a correlation of 0.815, for the A horizons of soils across a humidity transect (250mm to 1000mm per annum) in Colorado, Kansas and Missouri. This is attributed by them to the increase of both clay content and organic matter with increasing mean annual rainfall. While conceding that their transect is generally more arid than the Natal midlands region of this study, the strong positive relationship obtained by Jenny and Leonard is the complete opposite of the strong *negative* relationship observed in the Natal midlands, for both A and especially B1 horizons, and in several other parts of the world (eg. Singer, 1966). In later research, Jenny *et al.* (1968) have related ECEC to MAP, but do not report specific significance levels for this particular relationship (or even the nature of the slope), other than to say that clay mineralogy correlated with climate and parent material. Singer (1966) has obtained a negative linear relationship between rainfall and apparent CEC for soils formed upon basalt in the Golan, Israel (Figure 19):

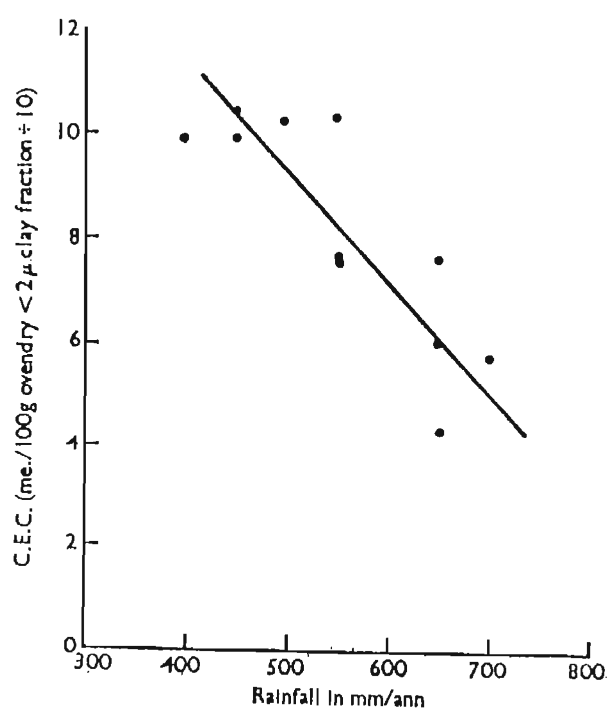

Figure 19. Relationship between cation exchange capacity of the clay fraction and mean annual rainfall for soils formed upon basalt in the Golan, Israel (after Singer, 1966).

This relationship is directly attributed by Singer to the change in the clay mineralogy observed in the climosequence, with decreasing amounts of montmorillonite and increasing proportions of sesquioxides in the clay fraction, with increasing mean annual rainfall. Alexander *et al.* (1989) have noted a correlation of -0.81 between MAP and what they term 'sum of exchangeable cations' (being the sum of the neutral 1M ammonium acetate exchangeable cations Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}, and unbuffered 1M KCl exchangeable acidity), being identical to the ECEC of Juo *et al.* (1976).

For the 33 sites of the Natal midlands climosequence, ECEC and its modifications (expressed per unit mass of soil or per unit mass of clay, and including or excluding the monovalent cations) are related to each other and to the climatic indices MAP, MAER, MAD[B1 horizon]. The relationships are summarized in the following correlation matrices, stratified according to the lithology of the parent material:

All soils (n=33):

1	MAP	1.00						
2	MAER	0.94^{***}	1.00					
3	MAD [B1 horizon]	0.84^{***}	0.81^{***}	1.00				
4	ln(ECEC)	$-.83^{***}$	$-.87^{***}$	$-.63^{***}$	1.00			
5	ln(ECEC/unit clay)	$-.77^{***}$	$-.78^{***}$	$-.54^{**}$	0.96^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.85^{***}$	$-.89^{***}$	$-.66^{***}$	0.99^{***}	0.95^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.80^{***}$	$-.82^{***}$	$-.58^{***}$	0.96^{***}	0.99^{***}	0.97^{***}	1.00
		1	2	3	4	5	6	7

Shale derived soils (n=13):

1	MAP	1.00						
2	MAER	0.98^{***}	1.00					
3	MAD [B1 horizon]	0.92^{***}	0.87^{***}	1.00				
4	ln(ECEC)	$-.73^{**}$	$-.78^{**}$	-.54	1.00			
5	ln(ECEC/unit clay)	$-.66^{*}$	$-.71^{**}$	-.47	0.99^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.80^{**}$	$-.84^{***}$	$-.62^{*}$	0.98^{***}	0.96^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.75^{**}$	$-.79^{**}$	$-.58^{*}$	0.98^{***}	0.98^{***}	0.99^{***}	1.00
		1	2	3	4	5	6	7

Dolerite derived soils (n=11):

1	MAP	1.00						
2	MAER	0.95^{***}	1.00					
3	MAD [B1 horizon]	0.88^{***}	0.79^{**}	1.00				
4	ln(ECEC)	$-.76^{**}$	$-.84^{**}$	-.57	1.00			
5	ln(ECEC/unit clay)	$-.70^{*}$	$-.76^{**}$	-.48	0.97^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.73^{***}$	$-.81^{***}$	-.53	1.00^{***}	0.96^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.67^{*}$	$-.74^{**}$	-.45	0.96^{***}	1.00^{***}	0.97^{***}	1.00
		1	2	3	4	5	6	7

Sandstone derived soils (n=9):

1	MAP	1.00						
2	MAER	0.95***	1.00					
3	MAD [B1 horizon]	0.79*	0.73*	1.00				
4	ln(ECEC)	-.98***	-.97***	-.75*	1.00			
5	ln(ECEC/unit clay)	-.95***	-.88**	-.67*	0.96***	1.00		
6	ln(Ca + Mg + acidity)	-.99***	-.97***	-.75*	1.00***	0.95***	1.00	
7	ln((Ca + Mg + acidity)/clay)	-.97***	-.89**	-.68*	0.96***	0.99***	0.97***	1.00
		1	2	3	4	5	6	7

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

The natural logarithm of ECEC expressed per unit mass of soil is particularly well related to the climatic indices. The relationship between ECEC and MAER is displayed in Figure 20.

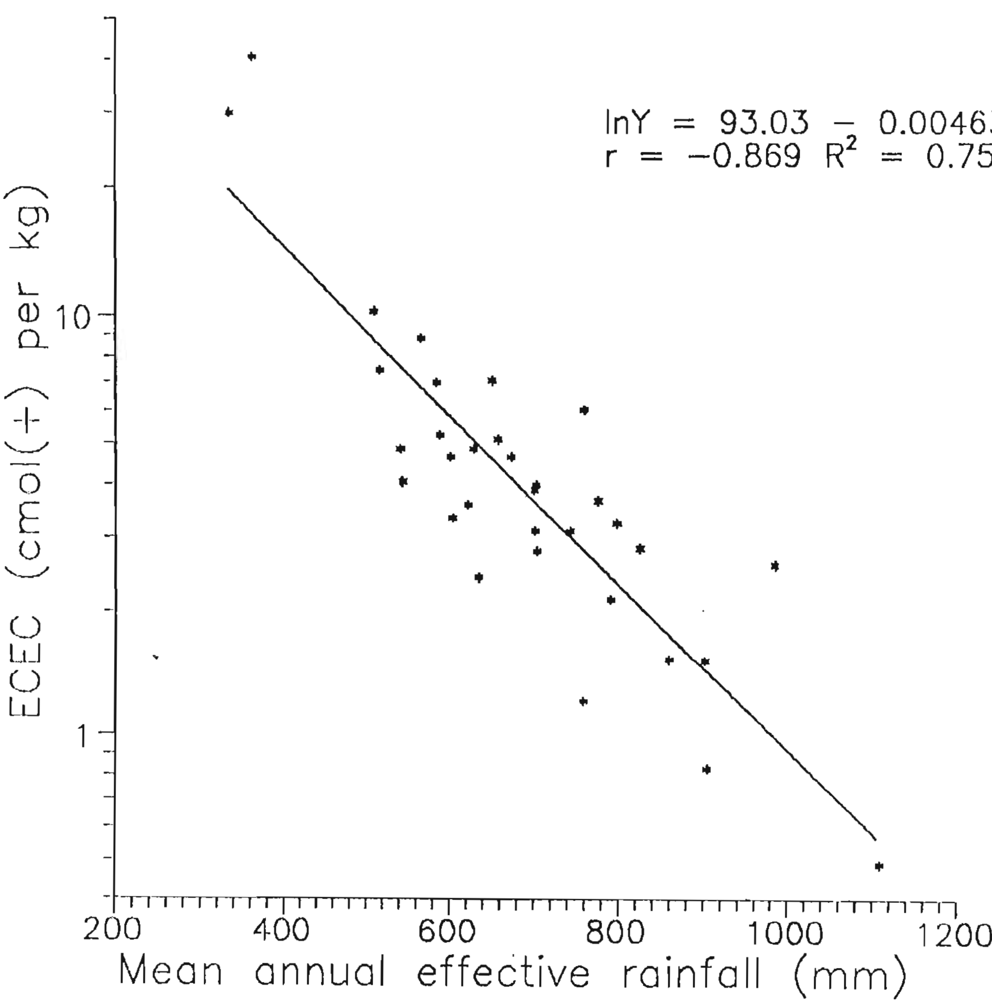

Figure 20. The relationship between MAER and ECEC for B1 samples from 33 sites the Natal midlands.

Excluding the monovalent cations K^+ and Na^+ from the calculation of ECEC results in a further improvement in the relationship with the climatic indices. For all 33 sites, there is a statistically highly significant relationship ($r = -0.89^{***}$, $p < 0.001$) between the natural logarithm of the sum of the exchangeable dibasic cations Ca^{2+} and Mg^{2+} plus exchangeable acidity and mean annual effective rainfall (Figure 21).

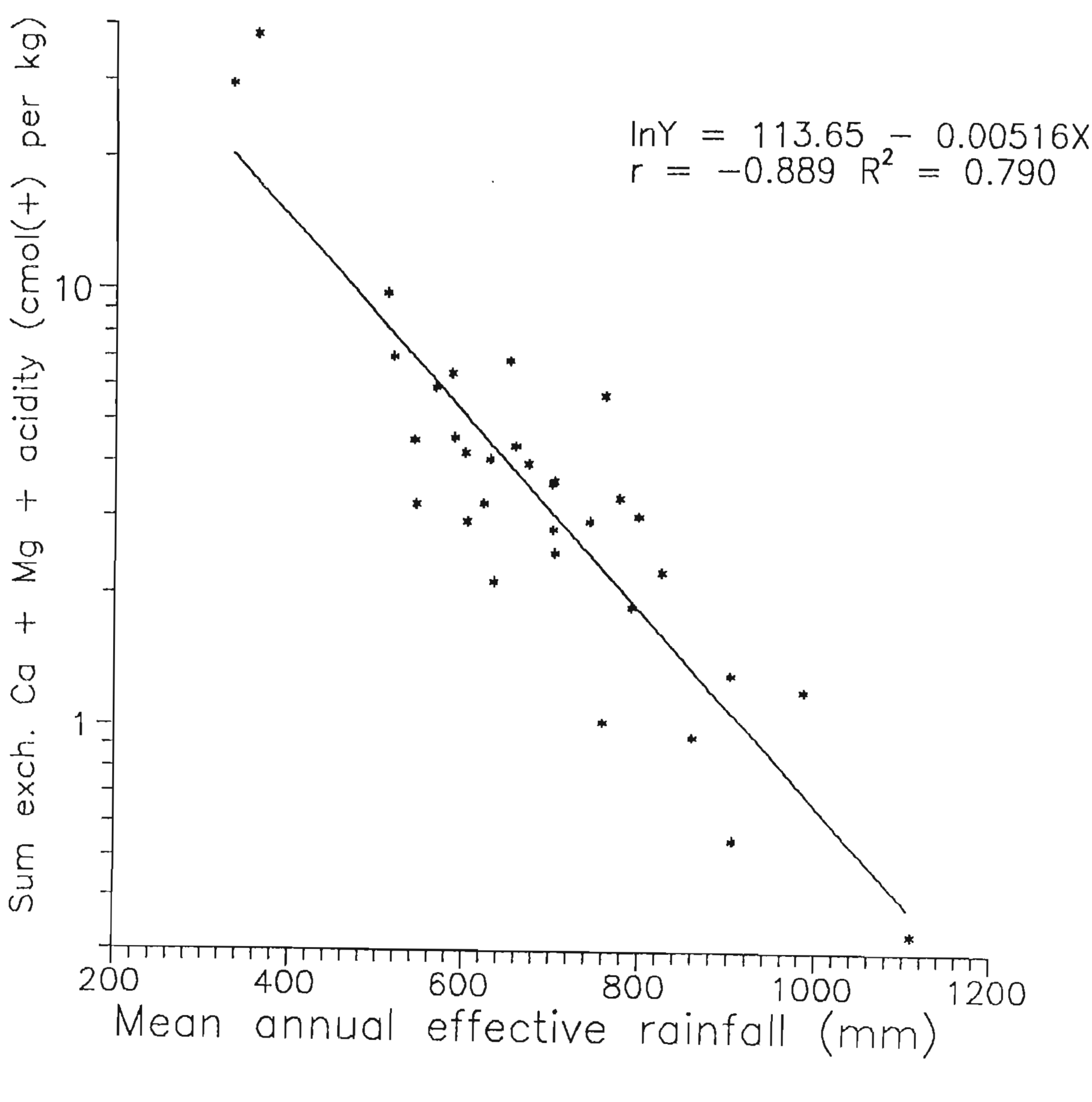

Figure 21. The relationship between MAER and Sum of exchangeable Ca^{2+} + Mg^{2+} + acidity per unit mass of soil for B1 samples from 33 sites in the Natal midlands.

For this particular relationship, the statistical analysis is as follows:

Linear model: Y = a + bX

Dependent variable - Log_e (Sum exch. Ca, Mg, acidity)

Independent variable - mean annual effective rainfall

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	4.7331	0.3364	14.0698	<0.0001
Slope	-0.005162	0.000477	-10.812	<0.0001

Analysis of Variance (ANOVA):

Source	Sum of Squares	Df	Mean Square	F-ratio	Prob.level
Model	22.61212	1	22.61212	116.899	<0.0001
Error	5.99640	31	0.19343		
Total (Corr.)	28.6085	32			

Correlation coefficient = -0.8890
Standard error of estimation = 0.4398 $cmol_c$ kg^{-1} soil
R^2 = 0.7904

For the purposes of prediction of the MAER, MAER is made the dependent variable and the soil property the independent variable, and the following regression results:

Linear model: Y = a + blnX

Dependent variable - mean annual effective rainfall

Independent variable - Log_e (Sum exch. Ca, Mg, acidity)

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	868.54	21.4136	40.56	<0.0001
Slope	-153.12	14.1619	-10.812	<0.0001

Analysis of Variance (ANOVA):

Source	Sum of Squares	Df	Mean Square	F-ratio	Prob.level
Model	670734	1	670734	116.899	<0.0001
Error	177868	31	5737.7		
Total (Corr.)	848603	32			

Correlation coefficient = -0.8890
Standard error of estimation = 75.748mm
R^2 = 0.7904

Stratifying the data set according to parent material (Figure 22) showed that there were no significant differences between the regression lines for the soils derived from the three parent materials.

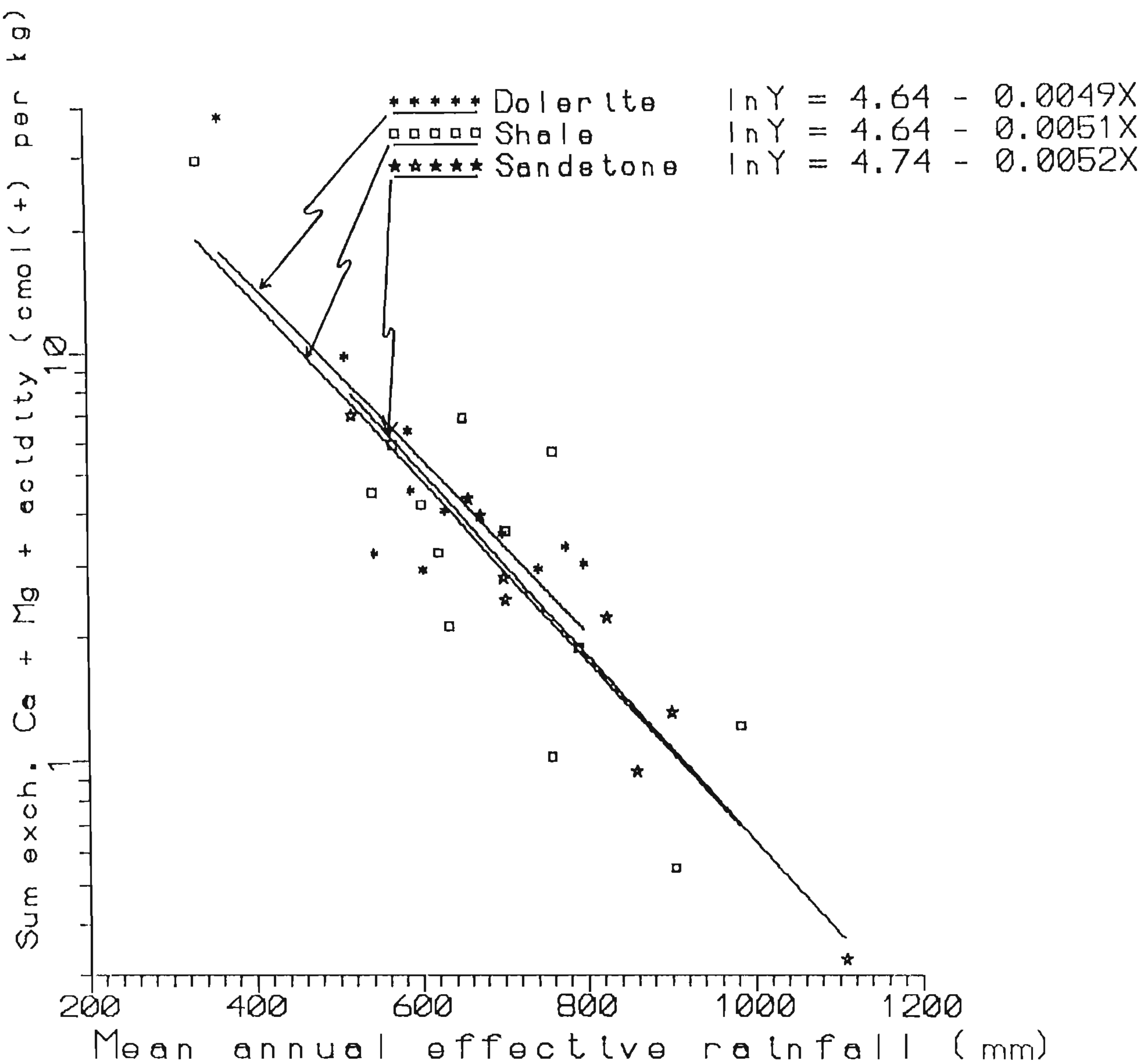

Figure 22. The relationship between MAER and Sum of exchangeable Ca^{2+} + Mg^{2+} + acidity per unit mass of soil for B1 samples from 33 sites in the Natal midlands, stratified according to lithology of the parent material.

If the ECEC is calculated as a function of the clay percent (sometimes termed *apparent CEC*), somewhat weaker relationships with climatic indices are observed (see correlation matrices, p.124-125). Again, as observed in section 4.1.1, the clay fraction may be considered to contribute substantially to the cation exchange capacity, but ECEC expressed per unit mass of clay does not improve on results obtained using ECEC expressed per unit mass of soil (and in fact is marginally poorer). Possible reasons for this anomaly are similar to those put forward for the equivalent S-value anomaly (section 4.1.1) and include the rôle played by soil organic matter in ECEC, independent of clay content, and the existence of exchange capacity on the silt and sand fractions. It must be noted that the relationship obtained by Singer (1966) between MAP and CEC per unit mass of clay was obtained after the destruction of the organic matter component with hydrogen peroxide. It is to be observed that the ECEC of organic matter is likely to decrease with increased soil acidity, as the degree of weathering increases and as the exchange sites become occupied to an increasing extent by (largely non-exchangeable) polyvalent cations, Al^{3+} and Fe^{3+}. The contribution to CEC of the soil by organic matter is not the same for all soils, or even per unit organic carbon content and cannot be assumed to be a consistent factor. Furthermore, adsorption of the soil organic matter on the clay surfaces will block a number of exchange sites, particularly at the periphery of microaggregates (Greenland and Hayes, 1981, p.12). Despite having 4.81% Walkley-Black organic carbon content in the B1 horizon of the highly weathered Qudeni profile, the ECEC of the horizon is only 0.49cmol$_c$ kg^{-1} soil (see Appendix A). In short, it is not unexpected that a measure of the degree of weathering, expressed per unit mass of *soil*, is better related to indices of climate, than the same measure of the degree of weathering expressed per unit mass of *clay*.

Since the specific surface area (SSA) of these soils had also been determined, using ethylene glycol monoethyl ether (see section 4.2.1, and Appendix B), the soil indices associated with ECEC were also expressed per unit surface area. Although a weak but significant relationship between clay content and SSA has been obtained ($r = 0.39^*$), the ECEC-associated indices were not notably improved when expressed per unit surface area, instead of per unit mass of clay, and did not match the performance of the same indices expressed per unit mass of soil. Again, it would appear that the SSA, at least when determined by the EGME method (Carter *et al.*, 1986), is not necessarily a reliable measure of surface reactivity as discussed in section 4.1.1.

4.2.2 Soluble silica

If it is assumed that clay minerals are in equilibrium with the soil solution, then the interrelations of the clay minerals may be presented as functions of the activities of their respective constituent ions in solution (Garrels and Christ, 1965, p.352). Thus the activities of relevant ions in solution are indicative not only of the clay minerals present, but also by implication, their concentrations are a measure of the extent to which a soil has undergone weathering, through the neoformation of these clay minerals. For example, it has been observed (Conyers, 1986) that for well-weathered Australian soils, large variations in Al solubility may be related to rainfall, with greater Al solubility being associated with higher rainfall. As a consequence of the kaolinite - gibbsite relationship, concentrations of Si in the soil solution should decrease with an increase in the leaching environment.

The equilibrium between kaolinite, gibbsite, silicic acid and water may be represented as follows[15]:

$$\underset{\text{kaolinite}}{Al_4Si_4O_{10}(OH)_8} + \underset{\text{water}}{10H_2O} = \underset{\text{gibbsite}}{4Al(OH)_3} + \underset{\text{silicic acid}}{4H_4SiO_4}$$

Under acid, well-drained conditions, silicic acid is essentially a neutral molecule and is readily leached. Therefore, under conditions of leaching, silicic acid is differentially removed from the system and, as a consequence of the principle of le Chatelier, the equation is driven to the right (Conyers, 1990).

For these well-drained, acid conditions, Conyers (1990) postulates a generalized equation for clay dissolution:

$$[X_a - Al_b - Si_c]_{clay} + dH^+ = bAl^{3+} + cH_4SiO_4^0 + aX^{n+}$$

[15]Formulae are taken from Brown (1990).

where [ ] represents a generalized clay mineral, and X represents non-Al cations. Conyers surmised that there would be an inversely proportional relationship between the activity of Al in soil solution and the activity of Si in solution, for surface soils, but subsequently modified the equation to take into account quasi-equilibrium conditions that pertain to open-system conditions, in which clay dissolution and Al solubility appear to depend on the relative rates of H^+ input and of silica leaching, and may also be modified by the presence and nature of organic matter in controlling Al solubility (Conyers, 1990). It has also been shown that the uptake of soluble silica by plants may be a substantial sink for the element (Trudgill, 1988, pp.131-132).

For the Natal midlands climosequence, the hypothesis that concentrations of soil solution Si may be indicative of the degree of leaching and/or the degree of weathering was investigated. The activity of silicic acid was determined for two separate extractions, being 1:2 soil:water; and 1:5 soil:0.01M $CaCl_2$, referred to as pH_4SiO_4 (H_2O) and pH_4SiO_4 ($CaCl_2$) respectively. Other soil solution properties, such as electrical conductivity (EC) and pH were determined for the 1:2 soil:water extraction. Analytical procedures were those of Weaver *et al.* (1971) and Hallmark *et al.* (1982) and are presented in Appendix B. Swindale and Uehara (1966) have shown that as mean annual rainfall increases, there is a shift in the values of the pH_4SiO_4 towards the kaolinite/gibbsite stability phase boundary. It is assumed that atmospheric inputs of Si to the soil system are negligible (Trudgill, 1988, p.130). It must also be assumed that the nature and magnitude of Si biocycling (through the production of phytoliths such as opaline silica) is such that it does not contribute greatly to the Si present in equilibrated soil solutions. Although the solubility of opaline silica is greater than quartz, it is less than amorphous silica (Trudgill, 1988, p.132). Interestingly, Scrivner *et al.* (1973) proposed to combine soil solution data for pH and the activities of Al and Si with a model describing soil moisture regimes, but reported that at the time [1973] this objective had not been achieved. No further work of this kind has been uncovered so far in the literature.

For the B1 samples from 33 sites around the Natal midlands, selected soil solution data were related to each other and with the climatic indices used previously (MAP, MAER, MAD[B1 horizon]) and the relationships are presented in form of correlation matrices:

All soils (n=33):

		1	2	3	4	5	6	7	8	9
1	MAP	1.00								
2	MAER	0.94***	1.00							
3	MAD [B1 horizon]	0.84***	0.81***	1.00						
4	pH_4SiO_4 (H_2O)	0.58***	0.60***	0.31	1.00					
5	pH_4SiO_4 ($CaCl_2$)	0.63***	0.65***	0.37*	0.87***	1.00				
6	pH (H_2O)	-.45**	-.52**	-.45**	-.18	-.34	1.00			
7	pH ($CaCl_2$)	-.26	-.38*	-.27	-.08	-.13	0.53**	1.00		
8	lnEC	-.45**	-.41*	-.30	-.37*	-.36*	0.01	0.34	1.00	
9	lnECEC	-.83***	-.87***	-.63***	-.72***	-.72***	0.37*	0.49**	0.57***	1.00

Shale-derived soils (n=13):

		1	2	3	4	5	6	7	8	9
1	MAP	1.00								
2	MAER	0.98***	1.00							
3	MAD [B1 horizon]	0.92***	0.87***	1.00						
4	pH_4SiO_4 (H_2O)	0.33	0.44	0.12	1.00					
5	pH_4SiO_4 ($CaCl_2$)	0.51	0.55*	0.30	0.86***	1.00				
6	pH (H_2O)	-.45	-.51	-.18	-.15	-.32	1.00			
7	pH ($CaCl_2$)	-.40	-.47	-.29	-.16	-.21	0.25	1.00		
8	lnEC	-.05	-.06	-.11	0.21	0.14	-.16	0.41	1.00	
9	lnECEC	-.73**	-.78**	-.54	-.64*	-.67*	0.11	0.55	0.35	1.00

Dolerite-derived soils (n=11):

		1	2	3	4	5	6	7	8	9
1	MAP	1.00								
2	MAER	0.95***	1.00							
3	MAD [B1 horizon]	0.88***	0.79**	1.00						
4	pH_4SiO_4 (H_2O)	0.49	0.58	0.36	1.00					
5	pH_4SiO_4 ($CaCl_2$)	0.40	0.53	0.15	0.87***	1.00				
6	pH (H_2O)	-.76**	-.87***	0.55	-.41	-.42	1.00			
7	pH ($CaCl_2$)	-.48	-.60	-.36	-.41	-.28	0.69*	1.00		
8	lnEC	-.53	-.64*	-.35	-.78**	-.66*	0.45	0.68*	1.00	
9	lnECEC	-.76**	-.84**	-.57	-.75**	-.63*	0.76**	0.79**	0.73*	1.00

Sandstone-derived soils (n=9):

		1	2	3	4	5	6	7	8	9
1	MAP	1.00								
2	MAER	0.95***	1.00							
3	MAD [B1 horizon]	0.79*	0.73*	1.00						
4	pH_4SiO_4 (H_2O)	0.85**	0.79*	0.49	1.00					
5	pH_4SiO_4 ($CaCl_2$)	0.78*	0.72*	0.43	0.93***	1.00				
6	pH (H_2O)	-.21	-.04	0.06	0.02	-.16	1.00			
7	pH ($CaCl_2$)	0.17	0.14	-.13	0.55	0.42	0.59	1.00		
8	lnEC	-.78*	-.67*	-.57	-.93***	-.85**	-.53	-.65	1.00	
9	lnECEC	-.98***	-.97***	-.75*	-.86**	-.75*	0.12	-.18	0.74*	1.00

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

Silicic acid levels in the 1:2 soil:water solution were generally higher than their counterparts in the 1:5 soil:0.01M $CaCl_2$ solution. Nevertheless there was a highly significant correlation between the amount of silicic acid extracted by the two extractants ($r = 0.87^{***}$, $p < 0.001$, for all 33 soils) and this was also observed to be constant across all parent materials (see correlation matrices, p.133).

For all 33 sites, relationships between MAER and levels of silicic acid (pH_4SiO_4) for the water and 0.01M $CaCl_2$ extracts are displayed in Figure 23.

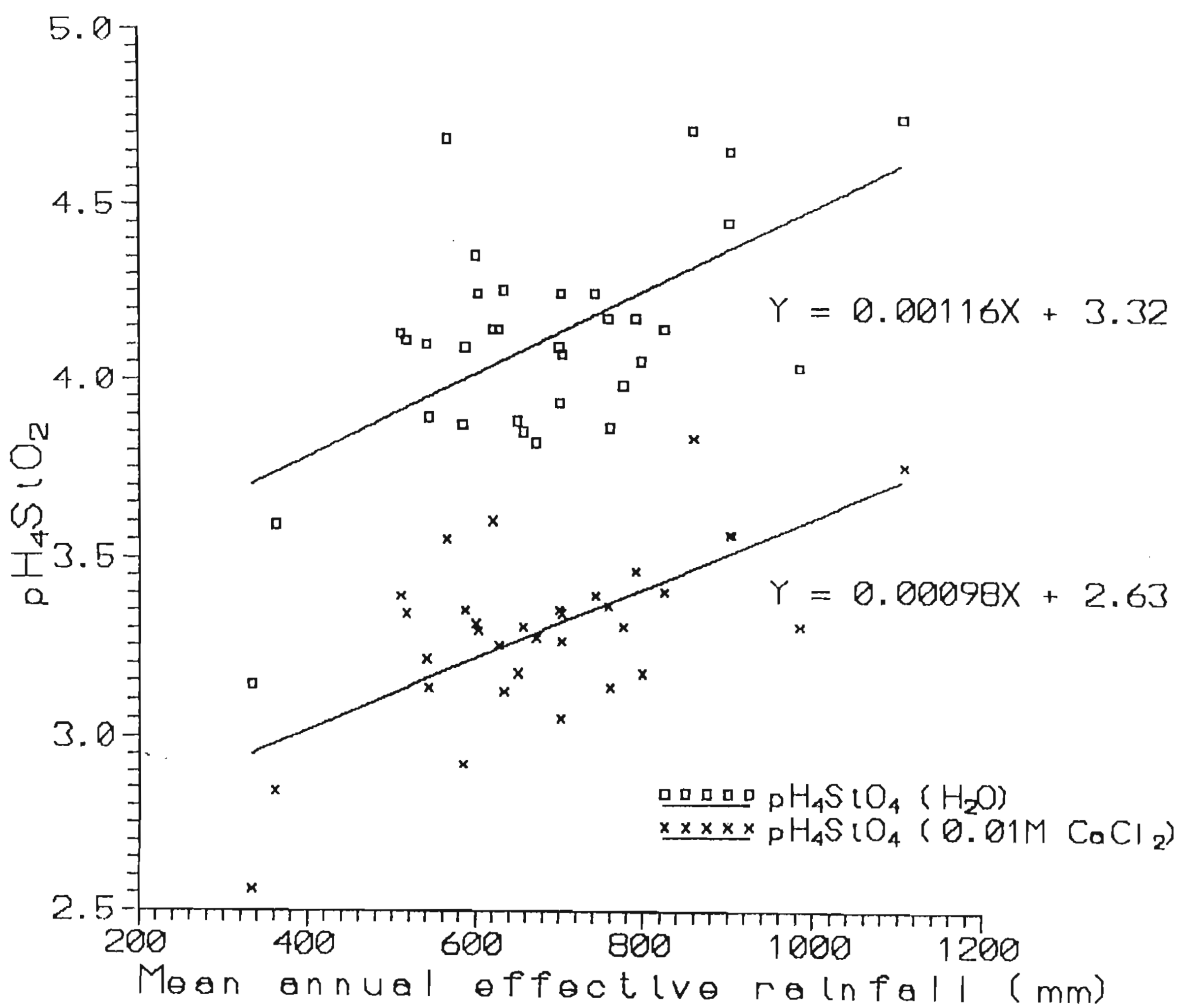

Figure 23. The relationship between MAER and pH_4SiO_4 (H_2O), and pH_4SiO_4 ($CaCl_2$).

Most of the soil solutions had concentrations of silica (expressed in terms of pH_4SiO_4) between the kaolinite/gibbsite stability phase boundary of 4.7 and the kaolinite/amorphous silica boundary. The kaolinite/gibbsite stability phase boundary is derived from thermodynamic considerations (Garrels and Christ, 1965, p.353), and the kaolinite/amorphous silica stability phase boundary has been observed experimentally at around values of 2.6 (Garrels and Christ, 1965, p.356), 2.72 (Weaver *et al.*, 1971), or 2.5 (Brown, 1990). Amorphous silica determines the upper limit of Si activity in soil matrix solutions. Thus the soils of this climosequence, as expected, fall into areas indicative of kaolinite stability in a stability phase diagram. That the relationships between soluble silica in the soil solution and indices of climate were not stronger may possibly be explained by the finding of Ranger *et al.* (1991) that silicate weathering proceeds in a series of episodic pulses, corresponding to the rainfall distribution. Given that the soils were sampled at different times of the year, this may have contributed to the variance in the data set. Non-equilibrium conditions in the soil may also have contributed to the variance. Smeck *et al.* (1983, p.51) consider the composition of the soil solution to be one that is:

> "...continually changing in response to nutrient uptake, weathering, adsorption-desorption reactions, leaching, or changes in moisture content of the soil."

This has also been discussed by Vedy and Bruckert (1982, p.193). These reasons may also be directed further in helping to explain why a measure such as ECEC is better related to climatic indices, than the potentially fluctuating *components* or *proportions* of ECEC, such as the S-value or base saturation.

From the correlation matrices (p.133) it is observed that when the sites are separated according to the dominant parent material from which each soil is derived, the relationships are particularly strong for those soils derived from the silica rich sandstone, but much weaker for those derived from dolerite and shale. There are also highly significant relationships between pH_4SiO_4 measured in the two equilibrating solutions and the natural logarithm of the effective cation exchange capacity (lnECEC) for the same soils, for all sites, and for each parent material.

The natural logarithm of electrical conductivity[16] (lnEC) is also shown to be statistically significantly related to the concentrations of silicic acid in both extracts and to the natural logarithm of ECEC (lnECEC) of these soils (see correlation matrices, p.133). Again, these relationships are particularly pronounced for the sandstone-derived soils, but are not statistically significant for the shale-derived soils.

The observation by Conyers (1990) that with decreasing pH (0.01M $CaCl_2$) there was a tendency (albeit weak) for sources of soluble silica to also decrease, was not apparent for this data set and no statistically significant relationship between the ratio (pH_4SiO_4 (H_2O)/pH_4SiO_4 (0.01M $CaCl_2$) used by Conyers to test for this trend and pH (0.01M $CaCl_2$) was observed.

Generally, pH measured in the 1:2 soil:water was related to a greater extent to indices of climate, than was pH measured in 1:5 soil:0.01M $CaCl_2$. Of interest again are the better relationships observed between the respective pH determinations with climatic indices for the doleritic soils compared to those for the shale-derived soils and for the sandstone-derived soils in particular. This is probably due to the base rich nature of dolerite, which will show a more ready response to weathering and leaching in terms of the lowering of pH, whereas shale and especially sandstone are much less base rich parent materials to begin with, and under equivalent conditions of leaching and weathering will not show as marked a decline in pH. This phenomenon has been dealt with in section 4.1.4.

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[16]The EC of a solution is an approximate measure of the total cation (or anion) concentration in the solution. It is approximate due to differences in the equivalent weights, equivalent conductivities, and proportions of major solutes in solution (Rhoades, 1986), but will certainly give a relative indication of ion concentrations in a comparison of soils.

4.2.3 Elemental ratios

The classical method prior to the 1930's for determining the extent to which a soil had undergone weathering, was through the determination of the relative abundances of silica and alumina or the sesquioxides (Buol *et al.*, 1989, p.76). Crowther (1931) quotes Robinson and Holmes (1924)[17] as having obtained an inverse relationship between the silica:sesquioxide ratio of the colloidal clay and rainfall, but not with temperature, at a number of sites around the United States of America; and Martin (1929)[18] who obtained an inverse relationship between the silica:alumina ratio of clay fractions and rainfall, for a set of soils from central Africa. Tanada (1951) obtained statistically significant relationships between various oxide ratios and the logarithm of mean annual rainfall, for the clay fractions of soils derived from basalt on Hawaii. More recently, Jenny (1980, p.332) has shown the narrowing of the silica:alumina ratio of soils with increasing mean annual rainfall in Hawaii.

Other elemental ratios have also been used, such as the molar ratio ($CaO + Na_2O + K_2O$)/($Al_2O_3 + CaO + Na_2O + K_2O$) which represents the alteration of feldspars (Kronberg and Nesbitt, 1981). For soils of a more advanced weathering stage, however, (such as those of the Natal midlands) in which the majority of the weatherable bases have already been removed (see XRF data in Appendix D), expressions based on the dominant residual elements (Si, Al and Fe) are more likely to form a useful basis for determining the degree of weathering than expressions derived from the already greatly depleted concentrations of alkali and alkaline-earth metals.

For the climosequence under consideration, total elemental concentrations were determined by X-ray fluorescence for the B1 soil samples from the 33 Natal midlands sites. Results were expressed in terms of the oxide percent of the non-volatile (1000°C) fraction (see Appendix D). From these results the silica:alumina ratios and the silica:sesquioxide ratios were calculated in terms of their molecular equivalents.

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[17]Robinson, W.O. and Holmes, R.S., 1924. *U.S.Dept. Agric. Bull.*, no.1311.

[18]Martin, F.J., 1929. *Conference of Empire Meteorologists*. vol.2, p.42.

Titanium oxide concentrations were also determined. Since it is generally assumed that the composition of the clay fraction reflects the degree of weathering, and that, at least in the more weathered soils, the non-clay fraction is dominated by quartz (SiO_2), the metal oxide concentrations of concern were recalculated for the clay fraction on the assumption that silt and sand consisted entirely of quartz (Appendix D).

Correlation matrices of the metal oxide ratios (of the soil as a whole, and of the clay fraction), soluble silica (determined in section 4.2.2), and climatic indices are presented, and are also stratified according to the parent material from which each soil was derived. Jenny has observed the influence of the parent material on the ratios in a weathering sequence (Jenny, 1941 pp.62-64).

All soils (n=33):

1	MAP	1.00								
2	MAER	0.94***	1.00							
3	MAD [B1 horizon]	0.84***	0.81***	1.00						
4	ln(SiO_2:Al_2O_3 (soil))	-.21	-.12	0.05	1.00					
5	ln(SiO_2:R_2O_3 (soil))	-.16	-.08	0.10	0.98***	1.00				
6	ln(SiO_2:Al_2O_3(clay))	-.50**	-.44**	-.22	0.68***	0.69***	1.00			
7	ln(SiO_2:R_2O_3(clay))	-.43*	-.38*	-.16	0.66***	0.70***	0.98***	1.00		
8	ln(TiO_2 (soil))	0.26	0.14	0.12	-.63***	-.71***	-.62***	-.68***	1.00	
9	pH_4SiO_4 (H_2O)	0.58***	0.60***	0.31	-.39*	-.37*	-.55***	-.52**	0.35*	1.00
		1	2	3	4	5	6	7	8	9

Shale derived soils (n=13):

1	MAP	1.00								
2	MAER	0.98***	1.00							
3	MAD [B1 horizon]	0.92***	0.87***	1.00						
4	ln(SiO_2:Al_2O_3 (soil))	0.14	0.13	0.25	1.00					
5	ln(SiO_2:R_2O_3 (soil))	0.34	0.34	0.49	0.81***	1.00				
6	ln(SiO_2:Al_2O_3(clay))	-.67*	-.74**	-.41	0.41	0.24	1.00			
7	ln(SiO_2:R_2O_3(clay))	-.63*	-.70**	-.36	0.40	0.30	0.99***	1.00		
8	ln(TiO_2 (soil))	0.15	0.13	0.05	-.02	-.35	-.22	-.31	1.00	
9	pH_4SiO_4 (H_2O)	0.33	0.44	0.12	-.45	-.36	-.80***	-.80**	0.12	1.00
		1	2	3	4	5	6	7	8	9

Dolerite derived soils (n=11):

1	MAP	1.00								
2	MAER	0.95***	1.00							
3	MAD [B1 horizon]	0.88***	0.79**	1.00						
4	ln(SiO_2:Al_2O_3 (soil))	-.50	-.44	-.30	1.00					
5	ln(SiO_2:R_2O_3 (soil))	-.47	-.45	-.27	0.98***	1.00				
6	ln(SiO_2:Al_2O_3(clay))	-.35	-.23	-.40	0.24	0.58	1.00			
7	ln(SiO_2:R_2O_3(clay))	-.19	-.13	-.30	0.04	0.06	0.94***	1.00		
8	ln(TiO_2 (soil))	-.04	-.07	0.08	-.35	-.44	-.05	-.15	1.00	
9	pH_4SiO_4 (H_2O)	0.49	0.58	0.36	-.60	-.68	0.15	0.18	0.35	1.00
		1	2	3	4	5	6	7	8	9

Sandstone derived soils (n=9):

1	MAP	1.00								
2	MAER	0.95***	1.00							
3	MAD [B1 horizon]	0.79*	0.73*	1.00						
4	$\ln(SiO_2:Al_2O_3$ (soil))	-.45	-.31	-.04	1.00					
5	$\ln(SiO_2:R_2O_3$ (soil))	-.45	-.32	-.05	1.00***	1.00				
6	$\ln(SiO_2:Al_2O_3$(clay))	-.77*	-.71*	-.32	0.88**	0.87**	1.00			
7	$\ln(SiO_2:R_2O_3$(clay))	-.76*	-.68*	-.30	0.89**	0.89**	0.99***	1.00		
8	$\ln(TiO_2$ (soil))	0.72*	0.60	0.43	-.86**	-.88**	-.88**	-.90***	1.00	
9	pH_4SiO_4 (H_2O)	0.85**	0.79*	0.49	-.67*	-.68*	-.84*	-.84**	-.84**	1.00
		1	2	3	4	5	6	7	8	9

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

It is to be noted that the relationships between the silica:alumina and silica:sesquioxide ratios for these soils as a whole, and for each parent material group, are extremely close, and consequently relationships obtained between these respective ratios with climatic indices were very similar.

In general, no statistically significant correlations were obtained between the whole soil silica:alumina ratio, silica:sesquioxide ratio, or the titanium oxide content, with climatic indices. The silica:alumina and silica:sesquioxide ratios of the clay fraction, however, did result in statistically significant relationships with the climatic indices, but only for those soils derived from shale and sandstone.

If it is assumed that each parent material is characterized by silica:alumina, silica:sesquioxide ratios and titanium oxide contents which are relatively invariant, then the respective metal oxide properties of the soils and clay fractions *relative to those of the original parent material* might enable these soil properties to be compared on a common basis, across all three parent materials. Mean figures for the oxides of Si, Fe, Al and Ti, for dolerite, shale and sandstone from the region, were extracted from sets of analyses presented in a Geological Survey publication: *Analyses of Rocks, Minerals and Ores* (1964). For these parent materials, silica:alumina and silica:sesquioxide ratios were calculated (see Appendix D). As in theory a soil should weather from a silica:alumina or silica:sesquioxide ratio of the parent rock to a ratio of zero (assuming no inputs of silica to the system), the respective ratios for each soil, and also respective ratios for the clay fraction of each soil, were divided by the equivalent ratios for the parent material from which each soil was presumed to be derived, and these indices are also presented in Appendix D. While for some of the relationships, marginally better relationships were obtained by using the natural logarithm of the elemental ratios (as in the previous set of correlation matrices), this did not consistently occur in all cases, and for some relationships where negative values occurred, the natural logarithm could not be determined (see Appendix D). For the sake of comparison and consistency, only the untransformed ratios were used in the following correlation matrix.

All soils (n=33):

1	MAP	1.00							
2	MAER	0.94***	1.00						
3	MAD [B1 horizon]	0.84***	0.81***	1.00					
4	SiO_2:Al_2O_3(soil)/ SiO_2:Al_2O_3(rock)	-.41*	-.33	-.17	1.00				
5	SiO_2:R_2O_3(soil)/ SiO_2:R_2O_3(rock)	-.41*	-.32	-.14	0.96***	1.00			
6	SiO_2:Al_2O_3(clay)/ SiO_2:Al_2O_3(rock)	-.65***	-.61***	-.39*	0.49**	0.51**	1.00		
7	SiO_2:R_2O_3(clay)/ SiO_2:R_2O_3(rock)	-.62***	-.59***	-.38*	0.44*	0.49**	0.97***	1.00	
8	TiO_2(soil)/ TiO_2(rock)	0.26	0.14	0.12	-.30	-.32	-.15	-.15	1.00
		1	2	3	4	5	6	7	8

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

Highly significant ($p<0.001$) correlations between these new ratios, the SiO_2:Al_2O_3 and SiO_2:R_2O_3 ratios of the clay fraction, relative to those of the original parent material, were obtained (for example r = -0.61*** for SiO_2:Al_2O_3 with MAER). This relationship between the silica:alumina ratio of the clay fraction relative to that of the parent material, with MAER, is presented graphically in Figure 24.

Of all the first-row transition metals, titanium oxide has been observed to be an accumulated element in the soil due to the relative depletion of other elements (Dawson *et al.*, 1991). Anatase and rutile are relatively immobile due to the very low solubility of the TiO_2. Therefore, the net relative accumulation of titanium oxide is potentially another index of weathering. Even though titanium is reported to be even less mobile than alumina and the sesquioxides, it is, however, present only in small amounts (< 3%) and as such, sampling and analytical errors for this index are relatively high (Young, 1976, p.98). Nevertheless, the natural logarithm of the net accumulation of titanium oxide in the soil, relative to the original parent material[19] (TiO_2 (soil)/ TiO_2 (parent material)) resulted in a statistically significant relationship with indices of climate (r = 0.479** with MAER). These relationships are, however, no better than the relationships achieved with the $SiO_2:Al_2O_3$ and $SiO_2:R_2O_3$ ratios (see previous correlation matrices). Further discussion of these findings is presented in Chapter 6.

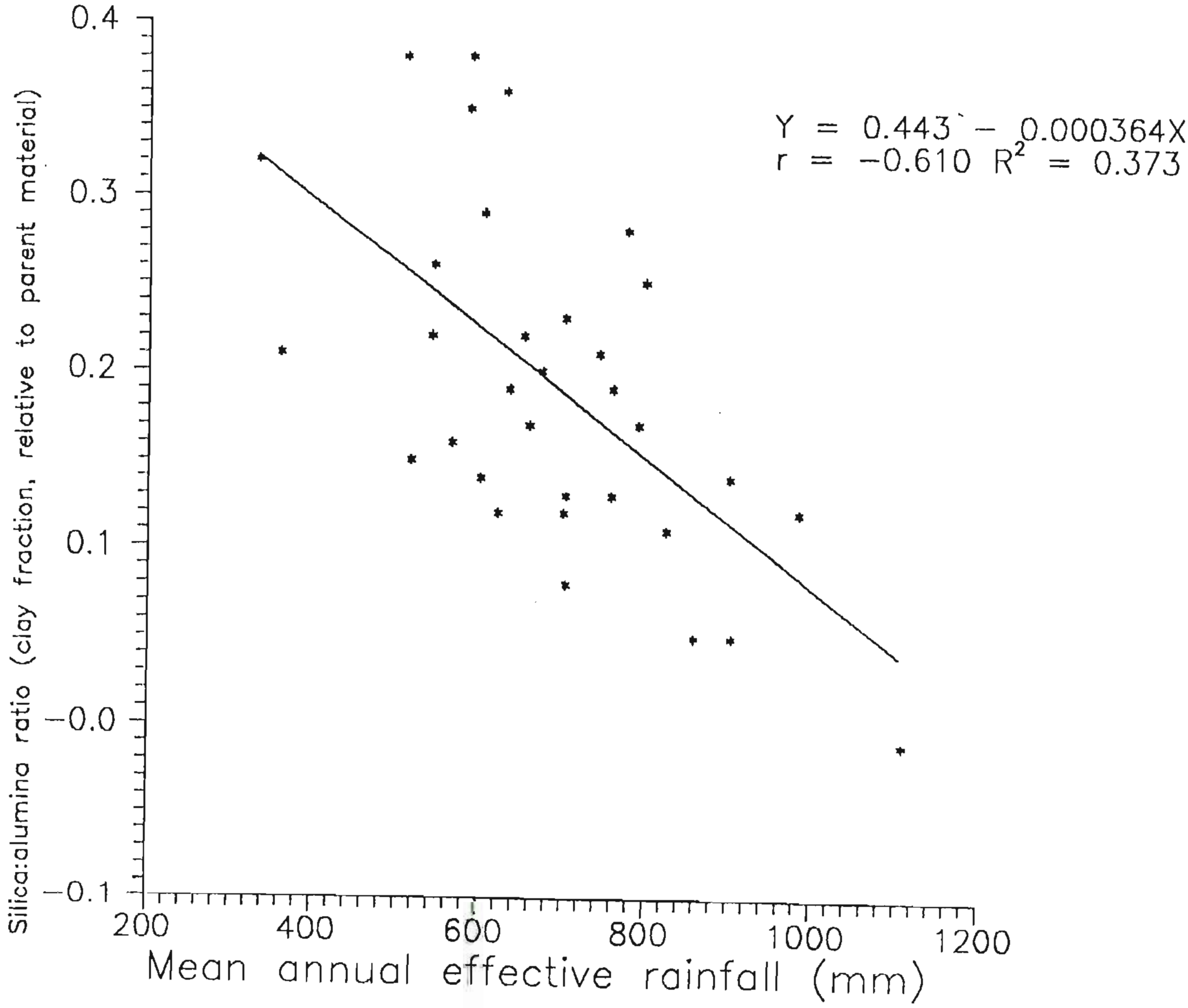

Figure 24. The relationship between MAER and $SiO_2:Al_2O_3$(clay)/ $SiO_2:Al_2O_3$(parent material) for B1 samples from 33 sites in the Natal midlands.

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[19]Figures taken from *Analyses of Rocks, Minerals and Ores*, Geological Survey, Pretoria, 1964.

CHAPTER 5 THE ESTIMATION OF AFFORESTATION POTENTIAL USING SOIL PROPERTIES

Introduction

There have been many attempts to relate tree growth to site characteristics and these have met with varying success. Considering the complexity of the site-tree system for all the different sites and different tree species, it is not surprising that a host of different solutions have been attempted and obtained, giving, at times, apparently contradictory interpretations. In general, best results have been obtained within limited areas (Grey, 1983) and are not easily extrapolated to other areas and other species.

Given that water availability is reported to be the prime determinant of tree growth in the summer rainfall areas of southern Africa (Grey *et al.*, 1987, p.73), it was anticipated that indices of leaching and/or weathering that had been found to be strongly related to indices of climate (detailed in Chapter 4), would also be related to timber site index in this region. The relationships obtained, however, between soil properties and timber site index by other researchers have given varied results.

As examples, Venialgo *et al.* (1988) have shown that the mean annual volume increase for pines in Corrientes, Argentina, is negatively correlated with cation content, particularly calcium, silt content and pH. Mean annual height increase is also reported by them to be negatively correlated with electrical conductivity and with calcium carbonate concretions in the profile. Many of these soil properties may be considered to reflect the leaching that has taken place in the soil. Sys (1978) however, has preferred to use indices such as base saturation as indicators of soil fertility limitations. In a study of *Pinus patula* in the Eastern Transvaal, Schutz (1990, p.121) has found that the site index of *P. patula* correlates *positively* with the exchangeable bases in the soil, particularly in the A horizon. Given that in the study by Schutz (1990, p.164), site index correlated *negatively* with rainfall (r = -0.48), the conclusion may be reached that for this tree species in this region, rainfall is not a limiting factor and that the positive correlation observed between site index and the exchangeable bases may be attributable to the importance of soil fertility. In a survey of the Umzimkulu District of Transkei, however, Grey (1978, p.193) found that there were no statistically significant relationships between selected soil variates and the site index of *P. patula*.

Page (1976) has shown that while soil moisture retention, nutrient availability, and organic matter accumulation are all implicated in determining the site indices for spruce and fir growth in Newfoundland, no single soil property explained a sufficient amount of the variability in the data sets used, to justify its use on its own. In fact it has often been found that there are no edaphic factors statistically significantly related to tree growth, with the exception of soil depth (Schönau and Aldworth, 1990).

Nevertheless, the objective of this portion of the study was to investigate the relationships of important selected soil indices of the degree of weathering and/or leaching (noted in Chapter 4) with timber site index, using a case study of a specific tree species (in this case *Acacia mearnsii* De Wild, commonly known as Black Wattle).

5.1 The requirements of forestry in the summer rainfall region of southern Africa

Climate and soil characteristics are considered to be the most important factors influencing tree growth in the summer-rainfall regions of southern Africa (Schönau and Grey, 1987). Yet attempts to establish relationships between soil properties and site index have been generally unsuccessful (Schönau and Aldworth, 1990).

Schulze (1982, p.130, in collaboration with Schönau) and Schönau and Grey (1987) have outlined the climatic requirements of the major timber species in Natal for optimum growth. The MAP requirements for selected tree species are presented as follows, but must be considered a rough guide, as the mean annual effective rainfall (which is more important than the MAP *per se*) is dependent upon a host of other factors, such as intensity and distribution of the rainfall, runoff, temperature regimes and the corresponding evapotranspiration.

Species	MAP (mm) criteria for optimum growth
Pinus patula	> 950
Pinus taeda	> 950
Pinus elliottii	> 900
Eucalyptus grandis	> 900
Eucalyptus macarthurii	> 850
Acacia mearnsii	> 850 and < 1200

Effective rainfall cannot be considered the sole index determining optimum tree growth for the different species. Further site requirements (such as temperature ranges, altitudinal criteria and minimum soil depths) have also been tentatively set (Schönau and Grey, 1987), but are not discussed here. Darby (1954, p.12), however, obtained a good correlation (0.635**, p<0.01) between mean annual rainfall and mean annual increment of bark yield for Black Wattle (*A. mearnsii*) (provided that favourable conditions of soil drainage prevailed), while Grey *et al.* (1987, p.73) have stated that for southern African soils, water is invariably the limiting growth factor rather than nutrients *per se*.

5.1.1 Current use of soil base status

The 1977 binomial soil classification used in South Africa (MacVicar *et al.*, 1977), defined the soil base status or degree of leaching according to the so-called S-value per 100g clay of the B21 horizon (see section 4.1.1), and this definition has been maintained in the 1991 soil classification (Soil Classification Working Group, 1991), with the exception that the B21 horizon is now referred to as the B1 horizon. Highly leached (dystrophic) soils determined on the basis of this S-value per 100g clay, are deemed desirable for afforestation as they are considered to occur in areas of high effective rainfall (Grey *et al.*, 1987). Mesotrophic soils have then been considered to be marginal for afforestation purposes, and eutrophic soils to be unsuitable for afforestation purposes. Schönau and Fitzpatrick (1981) have given the soil series of the 1977 soil classification (MacVicar *et al.*, 1977) suitability ratings for afforestation by a selection of common commercial species. In this paper, soil base status (amongst other criteria) is used actively to rate soil series in terms of their afforestation potential. Schönau (*pers. comm.*, March 1991) placed a tentative upper limit of 10cmol$_c$ kg^{-1} clay (within the mesotrophic class), above which afforestation is considered to be commercially unviable. While not generally used as a first cut indicator, it has often been used as a broad guide to the afforestation potential of an new area, and is used specifically when an area is considered to be marginal for afforestation and other indicators of afforestation potential (such as vegetation) are inconclusive.

In the light of the relationships obtained between the S-value, expressed per unit mass of clay, and indices of climate, including effective rainfall (Donkin, 1989; and detailed in section 4.1.1), it is of concern that a number of soil surveyors, forestry consultants and managers have placed much store in the S-value per unit mass of clay, and have been influenced by it in estimating the afforestation potential of areas, particularly those of marginal potential. Until now, no other soil properties indicative of afforestation potential have been considered, since there have been no tested alternative measures of the degree of soil leaching and/or weathering, or of their relationships with the effective rainfall of a site.

5.2 A test case: relationships between site index for Black Wattle (*Acacia mearnsii* De Wild) and soil properties relating to degree of leaching and/or weathering

Schönau (1969) undertook a site evaluation study in black wattle (*Acacia mearnsii* De Wild) with a major objective being the assessment of the contribution of site factors to tree growth.

With the availability of the raw data pertaining to the study, and of the original soil samples, and with the researcher (the late A.P.G.Schönau) still resident at the Institute for Commercial Forestry Research (ICFR), this set of circumstances provided an ideal opportunity to test aspects of the soil property - climate relationships described in

Chapter 4, and the manner in which they relate to tree growth, for this particular tree species.

The testing of relationships in the original study was dictated by the limited computing facilities available at the time, the nature of the routine soil analyses performed and by the availability and reliability of other site factors, such as climatic data. Several re-evaluations of the study have subsequently taken place (Schönau, 1988; Schönau and Aldworth, 1990).

Schönau (1969) in his site index study had 115 sites, termed first order sites, at which he related soil and site properties to tree growth. As the relationships obtained between soil properties and climatic indices in Chapter 4 pertained specifically to the B1 horizon, the data and soil samples for those sites in Schönau's study with similar soils (i.e. with chromic B horizons), were extracted from the original 115 sites. A further 5 of these sites were considered as outriders by Schönau and Aldworth (1990), due to the uncertain age and thus the site indices of the wattle stands on these sites, and were therefore also excluded from this analysis, leaving a total of 80 sites with the requisite characteristics.

Climatic, edaphic and topographic/geographic variables were related to site index. In the determination of soil properties in the original study (Schönau, 1969, p.124), CEC was determined by the ammonium acetate displacement method (pH 7). As is discussed in section 2.4.2 and 4.2.1, this method is no longer considered appropriate for the variable charge soils generally encountered in the summer-rainfall forestry regions of southern Africa. In the original study, exchangeable basic cations were determined on the leachate from the CEC determinations. Textural analysis had been performed using a hydrometer. Consequently, it was decided that soil analyses for exchangeable cations, ECEC and soil texture would be repeated on the relevant soils according to the methods used for the rest of this study, as outlined in section 2.4 and in Appendix B. That the soil samples were taken and stored approximately 20 years ago, was initially considered a cause for concern, but the correlation between the sum of exchangeable basic cations determined by Schönau (1969) for the B1 samples for the 80 sites, and determined subsequently in the laboratories of the ICFR over 20 years later, was statistically highly significant ($r = 0.949^{***}$, $p<0.001$) with no evidence of bias or skewness in the results relative to each other. The correlation between B1 clay content determined by Schönau (1969) and the subsequent values obtained over 20 years later in our laboratories, also had a statistically highly significant correlation ($r = 0.925^{***}$, $p<0.001$), although there was a significant bias in the results, values being consistently some 8.5% higher in the later determinations. This bias may be attributed to the enhanced dispersion of the soil brought about through the sonication process used currently in our laboratories (see Appendix B), compared to the mechanical "milkshake-mixer" used in the original study.

Schönau also correlated Effective Rooting Depth (ERD) with site index. This measure of rooting volume and water storage capacity is a strong determinant of tree-growth potential (Grey *et al.*, 1987, p.73). ERD is defined as the distance from the surface to the first horizon considered to offer obstruction to tree root penetration. Although not considered by Schönau in the original study, for the purposes of this re-evaluation, the Available Water-holding Capacity (AWC) was also calculated for each horizon and summed for each profile, using the regression equations developed by Hutson (1984) for estimating soil field capacity and wilting point, based upon soil textural data. Alexander *et al.* (1989) have found AWC to be a highly significant predictor variable of timber yield index. Nemani and Running (1989) have also used soil water-holding capacity in conjunction with an index of climate in the prediction of leaf area index (LAI), the ratio of leaf area per unit ground area, for mature stands of timber.

Site index in this study was expressed in terms of the arithmetic mean height of a wattle stand at 10 years of age (Schönau, 1969, p.135). MAP as used by Schönau (1969) in the black wattle study is actually the mean annual rainfall measured over the life-span of the stands in question, and were obtained from farm and estate records of the time (Schönau, 1969, p.137), and is referred to as Schönau's MAP (MAP-S) for the remainder of this chapter. As such, there is considerable potential for the deviation of MAP-S (being dependent on the whims of nature) from the actual long-term Mean Annual Precipitation as used in the context of the rest of this thesis.

The relationships between site index, MAP-S, ERD, AWC and selected soil properties related to soil leaching and weathering, are presented in the form of a correlation matrix:

For all sites with apedal, chromic subsoils (n=80):

1	Site Index	1.00							
2	MAP-S	0.32**	1.00						
3	ERD	0.39***	0.04	1.00					
4	AWC	0.37***	0.32**	0.67***	1.00				
5	Base sat.%	0.32**	0.05	0.28*	0.22	1.00			
6	ln(Ca+Mg+acidity)	0.08	-.17	-.17	-.16	-.14	1.00		
7	ln(S-value/clay)	0.19	-.10	0.00	-.08	0.60***	0.55***	1.00	
8	ln(ECEC)	0.08	-.17	-.16	-.16	-.12	1.00***	0.56***	1.00
		1	2	3	4	5	6	7	8

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

Of the site factors represented here, a cross-product term, MAP-S*ERD, gave the best correlation with site index (r = 0.471***, p<0.001). In general, relationships with site index confirmed the results presented by Schönau (1969, p.144) and Schönau and Aldworth (1990). Of the site factors considered above on their own, only AWC was significantly related to MAP-S (r = 0.32**, p<0.01), and is probably due to increasing soil depth, and increasing clay content, which both combine to increase AWC, with increasing climatic intensity, and therefore increasing weathering. A strong correlation between ERD and AWC (r = 0.67***, p<0.001) was also noted and is due to the common soil depth term.

In the data set considered above, it was felt that some soils were not wholly representative of the soils encountered in the Natal midlands climosequence (Section 2.2.5 and Chapter 4). In order to obtain a soil set from the site index set that best approximated the soil set used in the climosequence, a further restriction was made, by excluding all those sites with soils that had soft or hard plinthic horizons, or deep (>40cm) humic A horizons. This left a reduced set with 38 sites.

The equivalent correlation matrix for this reduced subset, to the one for the 80 sites set, follows:

n=38

1	Site Index	1.00							
2	MAP-S	0.11	1.00						
3	ERD	0.36*	-.07	1.00					
4	AWC	0.36*	0.45**	0.44**	1.00				
5	Base sat.%	0.22	0.12	0.13	0.08	1.00			
6	ln(Ca+Mg+acidity)	0.08	-.34*	-.07	-.13	-.12	1.00		
7	ln(S-value/clay)	0.13	-.05	0.01	-.12	0.61***	0.57***	1.00	
8	ln(ECEC)	0.10	-.33*	-.06	-.12	-.11	1.00***	0.58***	1.00
		1	2	3	4	5	6	7	8

*, **, *** - significant at the 5%, 1%, and 0.1 % significance levels respectively

Of the site factors represented here, again the cross-product term of MAP-S*ERD gave the best correlation with site index (r = 0.383*, $p<0.05$). Again AWC is highly correlated with MAP-S, for the reasons given for the previous correlation matrix. For this set of sites, however, ln(ECEC) and the same term excluding the monovalent cations (ln(exch. Ca^{2+} + Mg^{2+} + acidity)) are significantly related to Schönau's MAP (r = -0.33* and r = -0.34*, $p<0.05$, respectively). These indices of a soil's degree of weathering have been highly related to climatic indices in Chapter 4. That these soil indices are significantly related to Schönau's MAP for this subset and not for the previous set of sites is an indication that sites with plinthic horizons have impeded drainage (distorting the effective rainfall - leaching/weathering relationship). Of particular interest are the low and non-significant relationships of the S-value per unit mass of clay with Schönau's MAP and with site index for both subsets of sites, which further discounts its use as an index of afforestation potential.

Given the low correlations of site index with Schönau's MAP, it would appear that rainfall is not a limiting factor on the majority of these sites. Schulze (1982, p.130, in collaboration with Schönau) reports that, in terms of rainfall, the optimum growth for black wattle in this region will occur in those areas with a MAP greater than 850mm, and that at MAP figures above 1200mm, there is slower bark maturation and a higher incidence of the gummosis disease complex. Given that the selection of 80 sites had a mean MAP-S of 1020mm, with a range of 791mm to 1557mm, and that the restricted set of 38 sites had a mean MAP-S of 1011mm, with a range of 822mm to 1557mm, the weak correlation obtained between site index and MAP-S is to have been expected. That soil properties which have been found to correlate highly with effective rainfall (Chapter 4), are not highly related to timber site index in a region where rainfall is not limiting, is therefore not unexpected. That the relationships are slightly positive, would in fact indicate a correlation of site index with the fertility at the sites, rather than the effective rainfall occurring at each site.

5.3 The boundary line approach

It has been observed that regression type analyses are of limited benefit in explaining the site index of tree species (section 5.1., and in particular 5.2 for Black Wattle). In general the inadequacy of yield models of many plant species based on regressions of soil and/or foliar nutrients has often been noted (Evanylo and Sumner, 1987). Beaufils (1973) has also stated that the interpretation of yield responses to experimental treatments is of limited applicability to field conditions where there are many uncontrollable and interacting factors that cannot be evaluated or fixed simultaneously. In an attempt to surmount these problems, Beaufils (1973) has sought to establish critical nutrient values or sufficiency ranges for any particular plant species using a method termed the Diagnosis and Recommendation Integrated System (DRIS). DRIS serves to determine standard values or norms from large data bases of field experimental work obtained under a wide range of conditions. For fuller details of the DRIS concepts and methodology, readers are referred to Walworth and Sumner (1987).

Evanylo and Sumner (1987) have made use of a closely related approach, the "boundary line approach" to determine soil nutrient optimum levels and have described the method as follows:

> "With this approach, the performance of the best in a sample is employed as a standard against which to judge the remainder on the

assumption that there are reasons other than chance which account for the superior performance of part of the population. The line defining the best performance in the population lies at the edge of the data, hence the name "boundary line", and occurs wherever a cause-and-effect relationship exists between two variables."

In practice, a scatter diagram of yield values is plotted against a component presumed to be influencing yield, for all the data accumulated and a line bounding the plotted values is constructed.

This approach may also be employed for the site index study data of Schönau (1969). If it is assumed that water availability is the prime determinant of tree growth in the summer rainfall areas of southern Africa (Grey *et al.*, 1987, p.73), then a soil property, sum of exchangeable Ca^{2+}, Mg^{2+} and acidity (as reported in section 4.2.1), being a strong estimator of water availability, may be plotted in the form of a scatter diagram against site index (yield) for Schönau's *A. mearnsii* data (Figure 25).

A boundary line was drawn for the data set, discounting the two points on the extreme right of the diagram. On examination, these two sites were found to have plinthic horizons. Poor drainage associated with plinthic horizons with the possible presence of saprolite in the apedal B horizon samples may account for the high base status at these two sites. The boundary line peaks at a value of $2cmol_c\ kg^{-1}$ and appears to bound all points (excluding the two outriders) within a sum of exchangeable Ca^{2+} + Mg^{2+} + acidity value of $5cmol_c\ kg^{-1}$.

If all those sites with deep humic horizons or with horizons signifying wetness are excluded (as in section 5.2), a reduced set of sites is obtained, with similar soil forms to those of the Natal midlands climosequence. Again, site index was plotted against sum of exchangeable Ca^{2+} + Mg^{2+} + acidity and a boundary line was constructed (Figure 26).

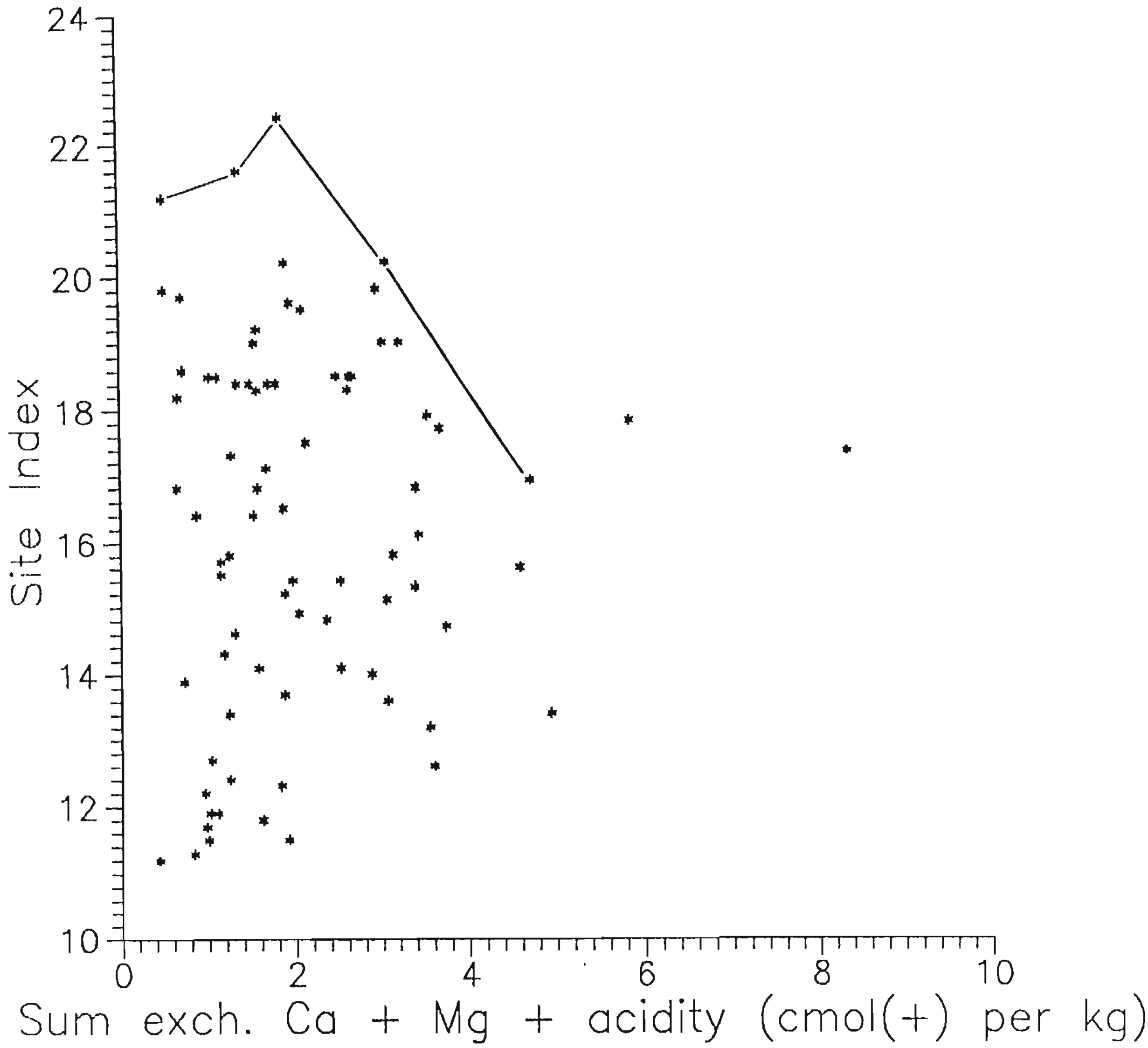

Figure 25. Site index of *A.mearnsii* versus Sum of exchangeable Ca^{2+} + Mg^{2+} + acidity for the 80 sites with apedal chromic subsoils.

For the restricted set of sites, there is no evidence of a peak or optimum value, but there are indications from the boundary line that yield drops as a value of 5cmol$_c$ kg^{-1} is approached. This value corresponds to a MAER of 600mm (Figure 21) and an MAP of approximately 800mm (Figure 25). This tends to confirm that the sites used by Schönau for his Black Wattle site index study are generally within what would be termed optimum growing areas for the species and that no markedly poor performing sites with low rainfall (<750mm) had been chosen, making it difficult to subject potential relationships between climatic indices and site index to a rigorous test.

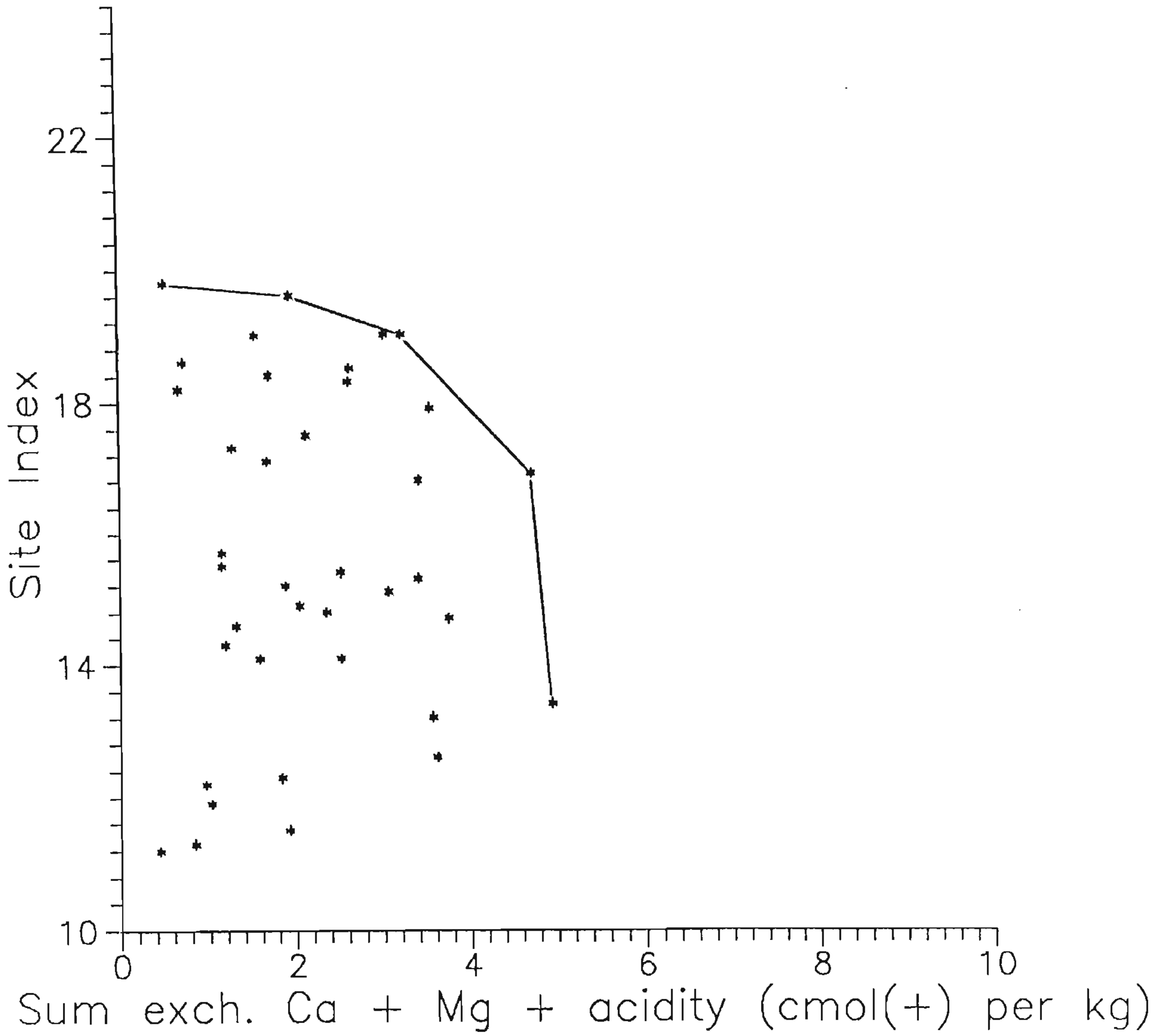

Figure 26. Site index of *A.mearnsii* versus Sum of exchangeable Ca^{2+} + Mg^{2+} + acidity for the restricted set of 38 sites without deep humic topsoils or diagnostic horizons signifying wetness.

As a general observation, it is recommended that any site index study should be based on sites distributed evenly across a wide spectrum of possible conditions and should not be restricted to occurrences within the historically established growing regions and conditions. Without such a distribution, site index studies or the boundary line approach will seldom test whether any particular factor is limiting and at which levels such factors become limiting. Of course this lack of foresight may also partially account for the poor performance of regression type models observed in section 5.1.

5.4 Conclusions

The weak relationship between indices of leaching and site index measured in Schönau's black wattle site index study, is not necessarily an indication that soil indices of leaching cannot be used for assessing afforestation potential in general, but that for the data set concerned (where rainfall is not limiting), factors other than climate (notably soil fertility) may be the over-riding influences on site index. Schönau and Aldworth (1990) have also concluded that relationships obtained between soil factors (other than ERD) and site index of black wattle, are due predominantly to soil fertility considerations. Schönau's MAP itself is only weakly correlated ($r = 0.32^{**}$) with site index, in the case of the 80 sample set, and does not significantly correlate with site index ($r = 0.11^{ns}$) in the case of the 38 sample subset (see correlation matrices). Of interest is the significant relationship between Schönau's MAP, and the natural logarithm of the sum of exchangeable Ca^{2+}, Mg^{2+}, and exchangeable acidity. That the correlation is not higher, as would be expected from the results of Chapter 4, may be attributed to the inadequate representation of long-term climatic conditions by Schönau's MAP data, and to the modifying effect brought about by the wattle afforestation on the soils themselves. Also of interest is the fact that the S-value per unit mass of clay data for both data sets correlated extremely weakly with both site index and MAP. This is further justification for the negation of the S-value as a tool in the determination of afforestation potential.

Ultimately, the usefulness of soil indices of the degree of weathering and/or leaching probably lies in the estimation of the mean annual effective rainfall of a site, particularly an uncultivated site. Such indices cannot be used for estimation of site index, simply because effective rainfall is not the sole, nor even necessarily the dominant, determinant of site index, for any tree species. Factors that need to be taken into consideration for the determination of a site's afforestation potential are, amongst others: soil depth, temperature, frost and snow occurrence, hail probability, altitude, cold-air drainage, rockiness, slope, and exposure to wind. Thus it is speculated that the greatest use for soil property - climate relationships is in the assessment of those virgin sites for which rainfall may or may not be limiting, and as such, the soil property - climate relationships will be of greatest use in the demarcation of the so-called climatically "marginal" sites. For such demarcations to be made for any particular tree species, site index studies of this nature should include sites normally considered unsuitable so that meaningful relationships between site factors and site index can be established, irrespective of whether regression type models or the boundary line approach is used.

CHAPTER 6 GENERAL DISCUSSION AND CONCLUSIONS

6.1 Pedogenesis

The principal objective of this research was to establish a procedure for estimating the mean annual effective rainfall of a site from soil properties at that site, as outlined in the Introduction. It was necessary that such research was performed within a conceptual framework or paradigm that enabled the formulating and choosing of research questions (Jacob and Nordt, 1991).

Given the nature of the climatic and soil data available, the only model of soil formation that could be readily applied to the description of soil property - climate relationships, was the conceptual state factor model of Hans Jenny (1941, 1980). Any relationships derived from such a model will in essence be empirical and not necessarily causal. Nevertheless, substantial success was attained in the description of such relationships, providing many relationships of a univariate nature, much sought after by Yaalon (1975) as steps towards the solving of a more generalised model of soil genesis. Considerable care had to be taken, however, in the selection of sites for the climosequence to ensure that the influence of other soil forming factors was minimised or observed to be constant.

A novel use of the state factor model of soil formation was made. While soil properties are in reality *dependent* variables of the state factors of soil formation, climate (c), organisms (o), topography or relief (r), parent material (p), time (t) and other unspecified factors such as the actions of man:

$$\text{Soil} = f(c,o,r,p,t,...)$$

for the purposes of this study, the state factor equations were *reversed*, in order to estimate a state factor (in this case indices of climate) from soil properties.

Climatic indices = f(Soil properties)

Only one other similar manipulation was uncovered after a thorough search of the literature, that being work done by Yaalon (1965, quoted in Yaalon, 1983, p.240) who found that for arid areas of Israel with inadequate climatic data, the effective rainfall can be estimated from the depth position of the maximum salt concentration in the soil. In the Natal midlands, a number of soil properties were found to be strongly related to indices of climate. The actual *use* of these relationships may realise a largely unprecedented *application* of results from experimental pedology.

The effect of climate as a soil forming factor is reflected principally through the processes of leaching and weathering. It is known that not only are these processes inextricably related, but it was established, using multivariate analyses, that soil properties indicative of leaching and/or weathering are highly covariant (see section 3.3). The concentrations of the exchangeable monovalent cations K^+ and Na^+, however, were demonstrated to be poorly related to the indices of leaching and weathering in general and as such may be considered as poor indicators of the influence of climate on pedogenesis.

A number of soil properties, regarded as indicating the extent to which soils have been leached and/or weathered, were related to various indices of climate, such as mean annual precipitation, mean annual effective rainfall and drainage occurring within the soil profile. Particular emphasis was placed upon measures of the exchangeable basic cations, exchangeable acidity, pH, soil solution composition, and various metal oxide ratios. Those soil properties indicative of cation exchange capacity (traditionally viewed as measures of the degree of weathering), were found to be best able to explain much of the variance in the climatic indices. Soil properties normally regarded as indices of the degree of leaching (such as base saturation, or the S-value per unit mass of clay) were less strongly related to the indices of climate. Other soil properties, however, also considered to be associated with degree of weathering such as the silica:alumina ratio of the clay fraction, were not as strongly related to the same climatic indices.

One might postulate that measures of the degree of leaching are more prone to seasonal fluctuations or fluctuations associated with moisture fronts in the profiles (resulting in regions of temporally concentrated and depleted base status), than some of the indices regarded as measures of the degree of weathering. The implication is that for freely-drained soils, properties associated with the cation exchange capacity (CEC) of the soil may be better indicators of some pedogenetic processes and/or the intensity of their driving variables, such as effective rainfall, than other soil properties (such as the S-value and base saturation) which depend on the occupancy of a relative *proportion* of the CEC, properties which may be much more transitory. Sampling of the sites in this study took place without regard to the time of year. Any other option would have been too restrictive in its applicability. Haines and Cleveland (1981) have demonstrated that seasonal variation in the concentrations of individual exchangeable cations is higher than the fluctuation associated with a measure of CEC on forestry and potential forestry sites in Georgia. As stated in section 4.2.2, Smeck *et al.* (1983, p.51) and Vedy and Bruckert (1982, p.193) consider the soil solution composition to be constantly changing in response to a number of processes, including changes in soil moisture content. Furthermore, Young (1976, p.270) considers the relative proportions of the exchangeable bases, their total amount (S-value) and therefore also base saturation, to be subject to change within the order of time of a decade, whereas he considers clay mineral type and thus cation exchange capacity to be considerably more persistent and to an extent irreversible. Herbillon (1981, p.91) has also observed that surface properties (such as CEC) are especially suited to describing the ultimate stages of weathering, when the bulk chemical and mineralogical compositions of soils show little further change.

In general, it was observed that relationships obtained between soil properties and climatic indices, did not markedly depend on the parent materials from which the soils were presumed to have been derived. An exception, however, was noted for the set of relationships between measures of soil acidity and climatic indices. The hypothesis that, all other things being equal, soils derived from base rich parent materials (such as dolerite) will possess a significantly higher base status than those soils formed from more acidic (and less base rich) parent materials (such as sandstone and shale) (Grey *et al.*, 1987, p.74) was not observed for this data set. This finding, however, does not discount the probability of obtaining such a distinction in regions more arid than that of this study. Van der Merwe (1941, p.312) has observed for the soils of the Mistbelt, relative to other parts of South Africa, that climate is the dominant soil forming factor, and that the soils of this region

> "...derived from igneous rocks (acid and basic) and sedimentary rocks (sandstone, shale and dolomite), are chemically, morphologically and genetically similar or related, due to the intensive weathering of the parent material caused by the high rainfall and high temperatures".

Another result of pedogenetic significance is that clay content (as a percentage of the soil) and soil specific surface area are not, *in themselves*, accurate measures of the *potential activity* of the soil. Although the clay fraction which may be expected to specifically reflect the extent to which weathering and/or leaching that has taken place, it was found that expressing cation exchange properties associated with both leaching and weathering in terms of "per unit mass of clay content" or "per unit surface area" did not explain more variance in indices of climate than those same soil properties expressed "per unit mass of soil". Herbillon (1981, pp.86-87) has also noted for tropical soils that clay content and specific surface area *per se* are not reliable indicators of the potential activity of a soil. Research is currently needed to establish the relative reactivities of clay fractions in different soils (Juo, 1981, p.55; see also section 4.1.1).

6.2 Estimation of climatic indices using soil properties

As stated previously, the principal objective of this research was to establish functional relationships between soil properties at a number of sites and the climatic indices at those sites, with a view to being able to estimate those climatic indices at future sites for which climatic data was not otherwise obtainable, by using the soil properties at the site. It is to be anticipated, however, that no soil property will be able to explain all the variance in any climatic index. The reasons for this may be summarized as follows:

i) Soil properties in the field display considerable variability. This variability (both systematic and random) is exhibited spatially and temporally. The spatial variability occurs not only in the plane of the earth's surface, but also with depth.

ii) The solution of climofunctions in general, or the equating of soil properties with indices of climate as in this study, demands that all other soil forming factors are constant, or vary to an extent that has negligible impact on the soil. In practice, this is never the case and at best, the effects of the other soil forming factors may only be minimal.

iii) The relationships obtained are empirical in nature.

iv) The characterization of climate as a soil forming factor is never known with absolute certainty. Climatic indices are usually based upon limited data sets that may not be truly representative of the climate over the time of soil formation, and climatic components, such as rainfall, are often underestimated through the methods of their measurement (as discussed in Scholes and Savage, 1989, p.8).

v) The soil properties determined may not be the most appropriate or the most responsive to climatic indices such as effective rainfall. The capacity of laboratory methods to measure such soil properties and the analytical errors incorporated in such analyses will also contribute to the variance in any observed soil property - climate relationships.

Nevertheless, some important conclusions may be reached about the relationships discussed in Chapter 4:

i) *Use of the S-value per unit mass of clay.* In a study of soils from 33 sites from around the Natal midlands, it was found that the currently used index of the degree of leaching in South Africa, the S-value, expressed per unit mass of clay (Soil Classification Working Group, 1991), is not sufficiently well related to climatic indices to enable reliable estimates of climatic indices to be made on the basis of this soil property. The derivation of estimates of climatic indices solely on the basis of the S-value per unit mass of clay involves a considerable risk of incorrect assessment.

ii) *Use of base saturation.* Base saturation has been mooted as a possible replacement for the S-value per unit mass of clay as a classification criteria (Soil Classification Working Group, 1991, p.41). Relationships of base saturation with climate, however, while showing general trends, were poor, although improved with the exclusion of the monovalent cations from the index. Indeed, the inclusion of the monovalent cations in any indices of base status for the purposes of predicting climate does not appear to be beneficial. Their exclusion from such indices not only accounts for more of the variability in climatic indices, but means that such new soil properties are less complex and are more easily determined. Base saturation, however, is not recommended for the purposes of estimating indices of climate and is generally regarded as an unreliable soil property, as outlined by van Wambeke (1987), Eswaran and Tavernier (1980, p.436) and discussed in section 4.1.2.

iii) *Use of an alternative soil property, the modified ECEC.* At these same sites, a considerable number of other soil properties were highly related to climatic indices. In particular, strong relationships were obtained between measures of the effective cation exchange capacity (ECEC) expressed per unit mass of soil and climatic indices, for the three parent materials encountered. The best relationship obtained, was that between a modified version of ECEC, being the sum of exchangeable Ca^{2+} + Mg^{2+} + exchangeable acidity, expressed per unit mass of soil[19], with mean annual effective rainfall (MAER). The relationship obtained is sufficiently strong to enable a reasonable estimation of the MAER of a site from the soil property and it may be advocated for this purpose. The

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[19]Sum of 1M ammonium acetate exchangeable Ca^{2+} and Mg^{2+} plus 1M potassium chloride extractable acidity determined by titration with 0.001M NaOH, expressed in terms of $cmol_c\ kg^{-1}$ soil.

equation for prediction of mean annual effective rainfall (MAER) from this soil property is:

$$MAER^{20} = 868.5 - 153.1 \ln (\text{Sum exchangeable } Ca^{2+} + Mg^{2+} + \text{acidity})$$

The standard error of estimation for this equation is 75mm. A further advantage of using the modified measure of ECEC is that whatever contribution is made by organic matter to the ECEC, is minimized under the acid conditions commonly encountered in the soils of the Natal midlands (Buol *et al.*, 1989, p.86).

It cannot be emphasised enough that the relationships obtained between soil properties and indices of climate in this study apply only to:

a) well-drained, permeable, chromic soils, occurring upon gently undulating (<5°) slopes;

b) sufficiently mature soils (although not palaeosols), displaying evidence of soil maturity such as profile horizonation;

c) uncultivated, or otherwise undisturbed sites (essentially virgin), that have not been subjected to any noticeable erosion or deposition;

d) soils derived from the three main parent materials of the study area *viz.* shale, sandstone and dolerite;

e) the Natal midlands, a region with a relatively high rainfall, where climate is regarded as the dominant soil forming factor. While such relationships may hold elsewhere in the humid summer-rainfall regions, such extrapolations would require confirmation.

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[20] Mean Annual Effective Rainfall (mm), as modelled by ACRU.

iv) *Indices of climate.* Generally, MAER as an index of climate resulted in only a marginal improvement over the use of MAP, in terms of its relationships to soil properties indicative of leaching and weathering. It would appear that within the restricted region of the Natal midlands, climate is largely related to the magnitude of the mean annual precipitation and is relatively independent of the other climatic modifiers, such as temperature, evapotranspiration and water runoff. It therefore follows, given the very good correlation between MAP and MAER ($r=0.94^{***}$, $p<0.001$) for the sites in this region (see section 2.3.2.4), that MAP may be used without major risk as an index of climate (within those regions where there is not a large range in the mean annual temperatures) *in the event that MAER cannot readily be determined.* Jenny *et al.* (1968) have found an even more highly significant relationship ($r = 0.997$) between MAP and an index similar to MAER, this being Arkley's leaching index *Li* (1963), a monthly sum of the positive values of monthly rainfall minus potential evapotranspiration, expressed over a yearly basis (see section 1.3.4.1). Despite being a gross climatic index, MAP has the advantages of being a more convenient index of climate, is readily available, is easily understood, does not necessarily require daily rainfall records, and is not model dependent.

Mean annual drainage from the B1 horizon (MAD [B1 horizon]) and from a soil depth of 50cm (MAD [50cm]), as modelled by ACRU as an index of climate, was, in general, weakly related to the soil properties of concern (see Chapter 4 and Appendix C). This was disappointing as the intention was to model the actual moisture carrying out the leaching on a mean annual basis. The poor performance of these drainage indices may be ascribed to the difficulty in modelling water movement within the profile, given the problems met in the quantitative description of concerns such as spatial variability in soil hydraulic properties, non-equilibrium processes and macropore flow. This is a problem encountered by all models of this nature (Wagenet, 1990).

6.3 Afforestation potential and soil properties

The weak relationships occurring between soil properties indicative of leaching and/or weathering and site index, observed for the site index case study for black wattle (*A. mearnsii*) by Schönau (1969) and found in many other site index studies, is not an indication that indices of leaching cannot be used for assessing afforestation potential, but that for the data sets concerned (where rainfall is not limiting), factors other than climate (notably soil fertility) may be the over-riding influences on tree site index. Schönau and Aldworth (1990) have concluded that relationships obtained between soil factors (other than effective rooting depth (ERD)) and the site index of black wattle, are due predominantly to soil fertility considerations. In fact, in this study, the mean rainfall, measured at each site over the growing span of the wattle stand, is only weakly correlated with site index (see section 5.2). Although the modified ECEC[21] (a measure of the degree of weathering) correlated significantly with rainfall, the S-value expressed per unit mass of clay correlated extremely poorly with both site index and rainfall. This finding provides further justification for the discarding of the use of the S-value per unit mass of clay as an indicator of a site's afforestation potential.

Given the incapability of regression type models to account for the site index of *A. mearnsii*, the "boundary line approach"[22] as used Evanylo and Sumner (1987) was applied to the data set (section 5.3), but results from this treatment were inconclusive and served only to confirm that water availability was not a limiting factor on most of the sites. It was concluded that site index studies of this nature should also contain a number of sites from outside the normal, established growing regions (where many of the factors that may well limit tree growth, are not limiting), so that those factors which may limit tree growth may be identified and the levels at which such factors

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[21]Sum of 1M ammonium acetate exchangeable Ca^{2+} + Mg^{2+} + unbuffered 1M potassium chloride extractable acidity, expressed per unit mass of soil.

[22]Yield (site index) is plotted against a component presumed to influence yield (in this case, the modified ECEC, as an estimator of a site's mean annual effective rainfall), and a boundary line to the scatter diagram is constructed, separating "real" values from "imaginary" values.

become limiting may be delineated.

Ultimately, the use of soil indices of the degree of weathering and/or leaching is in the estimation of the mean annual effective rainfall of a site, particularly for an uncultivated site. The use of such soil properties is not for the exclusive estimation of site index, as mean annual effective rainfall is not the sole, nor even necessarily the dominant, determinant of site index, for any tree species. Other factors that need to be taken into consideration for the determination of a site's afforestation potential have been listed in section 5.4. Thus the greatest use for soil property - climate relationships is in the assessment of those virgin sites for which rainfall may or may not be limiting, and as such, the soil property - climate relationships will be of greatest use in the demarcation of the so-called climatically "marginal" sites. The demarcation of those rainfall figures that are considered to separate climatically "marginal" from "sub-marginal" sites, however, is a task best left up to the forester, given that different tree species will have different minimum (or maximum) effective rainfall requirements, and will be aided by site index studies that also have sites occurring well outside the established growing regions.

6.4 Implications for soil classification in South Africa

In the South African soil classifications, soil base status has been defined in terms of the S-value expressed per unit mass of clay (MacVicar *et al.*, 1977, p.126; Soil Classification Working Group 1991, pp.40-41). Soil base status is assumed to be a measure of the leaching a soil has undergone, and thereby an expression of an index of climate. Statements concerning the implied [and thus the expected] relationships between soil base status and indices of climate, such as the following, have been made:

> "...In view of the wide climatic spread, the full range of base status is encountered: from highly acid and unsaturated to calcareous and salty soils" (MacVicar *et al.*, 1977, p.20).

The 1991 soil classification, however, admitted the lack of information needed to differentiate between soils at the series level, and

> "...so as to encourage scientists to generate the necessary information and define series levels, the second edition [1991] is restricted to that part of the system above the series level of the first edition [1977]" (Soil Classification Working Group, 1991, p.3).

In this regard, the results of this study go a long way towards the formulation of a working soil property that may be used as a differentiae for the purposes of distinguishing the degree of leaching and/or weathering, namely ECEC.

In fact, the classification has positioned itself for future changes:

> "As the information required becomes available, it is the intention to introduce a formal category, namely series, below the family, which will carry more information relevant to the land use than does the family" (Soil Classification Working Group, 1991, p.13),

and, as mentioned before, the 1991 classification system, in its definition of soil base status (Soil Classification Working Group, 1991, p.41), has suggested that:

> "Once sufficient data are available, it is possible that these criteria [S-value expressed per unit mass of clay] will be replaced by percentage base saturation."

The implication of this above statement is that a level of dissatisfaction or at least uncertainty with the current definition of soil base status has emerged. Nevertheless, in the absence of any tested alternative, the 1991 classification still makes use of the S-value, expressed per unit mass of clay, at the family level, although the use of this property is now restricted to those chromic B horizon soils overlaid by orthic A horizons having an organic carbon content less than 1.8%.

The implied relationships between soil properties, indicative of leaching and/or weathering, with indices of climate, is found in many soil classifications. For example, Soil Taxonomy (Soil Survey Staff, 1975, Chapter 2) states that attributes desired for series differentiation should, amongst other functions, be those that either affect soil genesis or result from soil genesis.

A further requirement for differentiae is that such soil properties should possess high information contents (i.e. should be highly related or covariate with a number of other important soil properties). Van Wambeke (1986), in a discussion of soil climatic data in Soil Taxonomy (USDA, Soil Survey Staff, 1975) states:

> "There have been lists of desirable attributes that differentiating characteristics should have: for example the developers of Soil Taxonomy selected their criteria on the basis of John Stuart Mill's logic saying that the properties "should, if possible, be those which are causes of many other properties, or, at any rate, which are sure marks of them"."

In addition, those properties that can be easily changed by land-use practices should be avoided (MacVicar, 1969). It may be added that it is also desirable that a property used as a soil differentiating criterion should not be subject to seasonal or other temporal fluctuations, as such properties may serve to make classification ambiguous.

Lastly, such a soil property should be easily and inexpensively measured, uncomplicated to use in practice, and easily understood both locally (within South Africa) and in the international community.

In respect of these requirements, it may be argued persuasively that the ECEC expressed per unit mass of soil may be considered to satisfy these criteria admirably (in preference to the S-value expressed per unit mass of clay, or base saturation), for the following reasons:

i) the ECEC, for well-drained soils of the Natal midlands, is more highly related, than the S-value per unit mass of clay (or base saturation), to indices of climate. Thus the property will possess greater pedogenetic significance. Indeed, given the evidence of Chapter 4, such a property may even be used to estimate indices of climate, within the constraints of this study (see section 6.2);

ii) the ECEC of a soil may be regarded as being less susceptible to change by land-use practices than other soil properties such as the S-value expressed per unit mass of clay and base saturation. Musto (1991)[23] has shown that for soils from the forestry regions of the summer-rainfall areas of South Africa, ECEC is a soil property that is not in general markedly altered by the practice of afforestation (due to the potentially opposing effects of humus accumulation and acidification (du Toit and Fey, 1992)[24]), whereas soil properties such as the S-value per unit mass of clay, pH and base saturation are significantly altered by such land use;

iii) the ECEC of a soil is less subject to seasonal or other temporal fluctuations or variability than other related soil properties such as the S-value or the base saturation (Young, 1976, p.270; Duchaufour, pp.403, 410). This has been discussed further in section 6.2;

iv) the ECEC of a soil is more directly related to the clay mineralogy of a soil than the S-value expressed per unit mass of clay, and is highly covariant with a number of other important soil properties (see sections 3.1.2 and 3.2.2.2); and

v) such a usage would bring about greater alignment with other soil classifications that also make use of measures of CEC. Indeed, no other soil classification system familiar to the writer makes use of soil base status defined in terms of the S-value per unit mass of clay.

It is encouraging to note that the 1991 revised South African soil classification already makes some use of a measure of cation exchange capacity. The use of CEC (pH 7 ammonium acetate) expressed per unit mass of soil is used to distinguish between "red apedal and neocutanic [B horizons] on the one hand, and red structured and

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[23]**Musto, J.**, 1991. *Annual Report*, Institute for Commercial Forestry Research, in press.

[24]**du Toit, B.** and **Fey, M.V.**, 1992. Soil acidification under forest plantations in Natal. *17th Congr. Soil Sci. Soc. S. Afr.*, Stellenbosch, January 1992. In press.

pedocutanic [B horizons] on the other" (Soil Classification Working Group, 1991, p.6). Red structured and pedocutanic B horizons are presumed to have a CEC greater than 11 $cmol_c$ kg^{-1} soil, on the assumption that structure, clay mineral composition and CEC will to large extent be covariant. This property is considered to be diagnostic

> "below any organic matter accumulation that forms part of the AB or BA horizon".

In the South African soil classification, CEC is used to indicate not only the presence or otherwise of 2:1 clay minerals, but "the kind and *amount of clay present*" (p.25). In all respects therefore, this parallels the thinking behind the revised FAO-UNESCO legend (FAO, 1988), which has replaced the former use of "apparent CEC" or CEC per unit mass of clay (FAO, 1974) by the use of CEC per unit mass of soil, as it was felt that dividing by the clay term did not accommodate influences due to factors such as organic matter (van Wambeke, 1989). As discussed in sections 4.1.1, 4.2.1 and 6.1, neither the clay content (as a percentage of the soil) or the specific surface area of the soil *per se* appear to be accurate measures of the *potential activity* of the soil, for soils of this region.

The results of section 4.1.2, taken in conjunction with the disparaging comments of Eswaran and Tavernier (1980, p.436) and van Wambeke (1989), suggest that base saturation is an unreliable differentia. It therefore is *not* recommended as a replacement index of soil base status, despite suggestions to this effect by the Soil Classification Working Group (1991, p.41). It should also be noted that Duchaufour (1977, p.403) regards CEC as a more useful and valid criterion for classification than base saturation.

Although the relationships obtained between ECEC and indices of climate were improved through the exclusion of the monovalent cations K^+ and Na^+ from the calculation of ECEC, for the purposes of soil classification, the recognised, unmodified usage of ECEC is advocated as a measure of soil base status, since this soil property may then be directly compared with other soil classifications and the international literature.

While the use of ECEC seems to be a worthwhile replacement for the S-value per unit mass of clay in the definition of soil base status, it does not resolve the question of: at which values or levels of ECEC do we make the "taxonomic chops"? It has been stated that the original intention of soil base status as a diagnostic property was to distinguish between ferrallitic and fersiallitic soils (R.F.Loxton, *pers. comm.*, Pretoria, July 1990). If this intention still holds for the South African soil classification, then it will require a detailed clay mineralogical study to delimit the groups of soils in terms of their ECEC, and further research and consideration will be required to decide upon those soil forms, families and/or series for which ECEC should be used as a diagnostic criterion. To arrive at any final recommendations for soil classification in South Africa does not fall within the scope of the present study.

Nevertheless, the implications of this research as a whole should go some way towards meeting the objections of Stoch (1976) who criticised (p.26) the South African soil classification system at that time for being based upon theory only and for the lack of *de facto* proof of claims made by the classification in respect of its applications in practice.

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APPENDIX A

Pit descriptions, summary of climatic data, and soil analytical data at each site.

Locality	Bloemendal Field Experimental Station
Station codes	239812 A; ATS0217
Lat.(S); Long.(E)	29°32'; 30°28'
Altitude	838m
Vegetation	*Aristida* grassland
Parent material	Ecca group shale (Pietermaritzburg formation)
Topography	Undulating 3° slope
Years of data	38
Record span in years	38
Reliability index[§]	1.00

Pit dug adjacent to entrance road next to Block 17 (E.Grandis)

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	description
A	0 - 20	Dry; brown (7.5YR 4/4); clay; apedal; porous; friable; frequent fine roots; gradual smooth transition.
B	20 - 100	Slightly moist; red (2.5YR 4/6); clay; apedal; porous; friable; frequent fine roots; abrupt transition.
R	100+	Shale.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	897.9	621.6	41.4	30.7
Median (mm)	886.8	643.4	31.0	20.3
Sample Std. Dev. (mm)	155.74	75.25	33.45	31.73
Minimum (mm)	628.0	468.1	0.1	0.0
Maximum (mm)	1447.6	780.2	122.1	113.1
Lower quartile (mm)	785.4	563.2	17.1	8.9
Upper quartile (mm)	978.8	666.5	52.6	41.7
C.V.%	17.35	12.11	80.81	103.19
Standardized skewness	2.45	-0.66	2.68	3.53
Standardized kurtosis	3.77	-0.39	0.72	1.63

[§]ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Bloemendal						
Horizon[1]	A	AB	BA	B1	B2		B3
Depth (cm)	0-5	5-15	15-35	35-50	50-65	65-80	80-100
pH (KCl)	3.9	3.9	4.0	4.2	4.6	4.7	4.4
pH ($CaCl_2$)	4.1	4.3	4.4	4.4	4.6	4.6	4.4
pH (H_2O)	4.8	5.0	4.9	4.8	4.9	5.1	4.9
Texture							
Clay %	61	64	66	76	81	83	80
Silt %	20	23	20	14	12	3	4
Sand %	19	12	13	10	7	14	16
Exch. cations $cmol_c\ kg^{-1}$							
Ca	0.52	0.81	0.96	0.72	0.32	0.36	0.07
Mg	0.49	0.56	0.71	0.79	1.16	1.12	1.03
K	0.19	0.13	0.08	0.09	0.08	0.08	0.06
Na	0.22	0.25	0.17	0.32	0.20	0.21	0.14
acidity	5.04	5.04	2.08	1.69	1.72	1.77	1.87
ECEC	6.46	6.79	4.00	3.61	3.48	3.54	3.17
C %	3.25	3.12	3.10	1.48	1.13	1.06	0.86
N %	0.20	0.17	0.13	0.07	0.07	0.05	0.05
C/N	16	18	24	21	16	21	17
S-val/(clay)	2.33	2.73	2.91	2.53	2.17	2.13	1.63
Base sat %	22	26	48	53	51	50	41
LOI (430°C)	15.5	11.7	10.2	9.8	9.6	8.8	8.4

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Windy Hill No.2
Station codes	0270119 W
Lat.(S); Long.(E)	29°29.5'; 30°33.7'
Altitude	960m
Vegetation	*Aristida* grassland
Parent material	Natal group sandstone
Topography	5° slope
Years of data	53
Record span in years	58
Reliability index§	0.91

Pit dug behind forestry office

Soil - Ma2100 sandy loam
Form - Magwa
Series - Lambasi

<u>Horizon</u>	<u>depth (cm)</u>	<u>Description</u>
A	0 - 55	Moist; dark brown (10YR 3/3); sandy loam; apedal; porous; friable; frequent fine roots; gradual smooth transition.
B	55 - 125	Moist; strong brown (7.5YR 5/6); sandy clay loam; apedal; porous; friable; frequent fine roots; gradual smooth transition.
C	125+	Sandstone saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	997.5	825.0	32.2	58.6
Median (mm)	969.8	802.0	16.1	38.1
Sample Std. Dev. (mm)	184.33	137.67	46.25	55.18
Minimum (mm)	572.2	478.0	0.0	0.0
Maximum (mm)	1599.6	1136.0	242.4	270.3
Lower quartile (mm)	866.5	725.0	1.88	22.9
Upper quartile (mm)	1125.8	922.0	42.35	80.2
C.V.%	18.48	16.69	143.41	97.17
Standardized skewness	1.85	0.00	7.82	5.49
Standardized kurtosis	1.77	-0.35	12.26	5.76

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Windy Hill

Horizon[1]	A		AB	B1	B2	
Depth (cm)	0-15	15-30	30-55	55-70	70-80	80-100
pH (KCl)	5.4	5.7	4.9	4.5	4.6	4.7
pH ($CaCl_2$)	6.0	6.3	5.4	4.9	4.8	5.1
pH (H_2O)	6.2	6.3	5.8	5.6	5.4	5.4
Texture						
Clay %	21	27	35	41	40	42
Silt %	15	14	10	9	10	10
Sand %	64	59	55	50	49	48
Exch. cations $cmol_c\ kg^{-1}$						
Ca	9.55	8.42	4.00	0.88	0.94	0.67
Mg	0.83	0.86	2.35	1.15	1.32	0.99
K	0.50	0.46	0.47	0.36	0.34	0.40
Na	0.07	0.07	0.07	0.07	0.09	0.08
acidity	0.42	0.24	0.31	0.26	0.36	0.26
ECEC	11.37	10.05	7.20	2.72	3.05	2.40
C %	2.37	1.96	1.57	0.83	0.55	0.55
N %	0.13	0.10	0.05	0.05	0.06	0.01
C/N	18	20	31	17	9	55
S-val/(clay)	52.14	36.33	19.69	6.00	6.72	5.10
Base sat %	96	98	96	90	88	89
LOI (430°C)	6.9	7.0	7.2	7.1	6.9	7.1

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Cedara Agricultural Research Station
Station codes	0239482 A; ATS0195
Lat.(S); Long.(E)	29°32'; 30°17'
Altitude	1067m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Dolerite
Topography	5° slope
Years of data	75
Record span in years	76
Reliability index§	0.99

At the meteorological site, a pit dug to 50cm, with auger samples taken at further depths.

Soil - Ma1200 clay
Form - Magwa
Series - Connemara

Horizon	depth (cm)	Description
A	0 - 30	Moist; strong brown (7.5YR 4/4); clay; moderate; fine; subangular blocky; porous; hard; common medium roots; gradual smooth transition.
B	30 - 120+	Moist; reddish brown (5YR 4/4); clay; apedal; porous; friable; common roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	877.2	700.9	115.6	115.6
Median (mm)	835.0	688.2	91.11	91.11
Sample Std. Dev. (mm)	191.92	129.54	92.85	92.85
Minimum (mm)	567.2	468.5	0.0	0.0
Maximum (mm)	1463.8	1075.7	421.7	421.7
Lower quartile (mm)	748.6	608.6	48.3	48.3
Upper quartile (mm)	977.8	790.3	175.0	175.0
C.V.%	21.88	18.48	80.34	80.34
Standardized skewness	4.01	2.29	4.38	4.38
Standardized kurtosis	2.19	0.12	2.33	2.33

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Cedara							
Horizon[1]	A		AB	BA	B1	B2		
Depth (cm)	0-10	10-20	20-30	30-45	45-55	55-70	70-80	80-90
pH (KCl)	5.2	5.2	5.0	4.8	4.7	4.7	4.7	4.6
pH ($CaCl_2$)	5.4	5.6	5.5	5.2	4.9	4.8	4.7	4.7
pH (H_2O)	5.8	6.0	5.8	5.5	5.2	5.4	5.2	5.3
Texture								
Clay %	24	42	40	57	59	51	54	50
Silt %	12	27	27	17	15	12	13	5
Sand %	64	32	33	26	26	37	34	45
Exch. cations $cmol_c\ kg^{-1}$								
Ca	3.82	3.67	3.20	2.80	2.65	2.40	2.34	2.30
Mg	1.31	1.29	0.84	0.43	0.42	0.41	0.55	0.67
K	0.64	0.55	0.23	0.16	0.14	0.11	0.10	0.08
Na	0.12	0.19	0.07	0.09	0.19	0.11	0.08	0.08
acidity	0.82	0.77	0.92	0.81	0.49	0.52	0.65	0.53
ECEC	6.71	6.47	5.26	4.29	3.89	3.55	3.72	3.66
C %	6.72	3.50	3.08	2.36	1.75	0.87	0.77	0.71
N %	0.42	0.29	0.17	0.13	0.09	0.11	0.05	0.06
C/N	16	12	18	18	19	8	15	12
S-val/(clay)	24.54	13.57	10.85	6.11	5.76	5.94	5.69	6.26
Base sat %	88	88	83	81	87	85	83	86
LOI (430°C)	17.8	12.9	12.7	12.0	11.2	9.5	9.1	8.5

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Dargle State Forest
Station codes	0239002 W
Lat.(S); Long.(E)	29°32'; 30°00.5'
Altitude	1280m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Dolerite
Topography	6° slope
Years of data	33
Record span in years	37
Reliability index§	0.89

Pit dug and samples taken just behind Met. office

Soil - Mg1100 clay
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	Description
A	0 - 30	Moist; dark yellowish brown (10YR 3/4); clay; apedal; porous; friable; frequent roots; gradual smooth transition.
B	30 - 120+	Moist; brown (7.5YR 4/4); clay; apedal; porous; friable; frequent roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	964.7	776.17	119.2	114.4
Median (mm)	944.0	788.5	111.0	105.8
Sample Std. Dev. (mm)	193.76	127.43	82.87	83.6
Minimum (mm)	492.0	407.0	5.6	5.6
Maximum (mm)	1425.0	1070.0	354.4	351.9
Lower quartile (mm)	828.0	702.0	51.2	46.4
Upper quartile (mm)	1079.0	843.0	156.6	149.2
C.V.%	20.08	16.42	69.50	73.09
Standardized skewness	1.09	-0.57	2.31	2.48
Standardized kurtosis	1.06	1.64	0.83	1.01

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Dargle

Horizon[1]	A	AB	BA	B1	B2				
Depth (cm)	0-10	10-30	30-40	40-50	50-60	60-70	70-80	80-100	100-120
pH (KCl)	4.5	4.1	3.8	3.8	3.8	3.8	3.9	3.9	3.9
pH ($CaCl_2$)	5.0	4.8	4.3	4.2	4.2	4.1	4.1	4.1	4.1
pH (H_2O)	5.7	5.8	5.1	5.1	5.1	5.2	5.5	5.3	5.2
Texture									
Clay %	49	41	49	55	52	54	57	57	59
Silt %	19	15	14	11	14	13	12	12	13
Sand %	32	44	37	34	34	33	31	31	28
Exch. cations $cmol_c\ kg^{-1}$									
Ca	8.93	4.84	1.34	0.89	0.89	0.69	0.64	0.52	0.55
Mg	2.18	1.59	0.48	0.25	0.35	0.30	0.34	0.26	0.23
K	0.92	0.51	0.20	0.18	0.15	0.15	0.13	0.15	0.16
Na	0.17	0.23	0.12	0.19	0.13	0.14	0.12	0.16	0.13
acidity	0.10	0.63	1.30	2.16	1.25	1.09	0.91	0.82	1.09
ECEC	12.30	7.80	3.44	3.67	2.77	2.37	2.14	1.91	2.16
C %	4.21	3.38	2.39	1.79	1.53	1.37	0.99	0.93	1.01
N %	0.28	0.22	0.14	0.10	0.08	0.09	0.06	0.06	0.08
C/N	15	15	17	18	19	15	17	16	13
S-val/(clay)	24.90	17.49	4.37	2.75	2.92	2.37	2.16	1.91	1.81
Base sat %	99	92	62	41	55	54	57	57	50
LOI (430°C)	13.7	12.2	10.7	10.5	9.8	9.8	9.4	9.4	9.3

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Ixopo police station
Station codes	0210099W
Lat.(S); Long.(E)	30°09.1'; 30°03.6'
Altitude	1029m
Vegetation	*Hyparrhenia* grassland
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Slope 7°
Years of data	46
Record span in years	58
Reliability index§	0.79

Profile exposed by house building operations 200m from police station. Bank cleared back and sampled.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	Description
A	0 - 30	Slightly moist; very dark greyish brown (10YR 3/2); clay; moderate fine subangular blocky; porous; hard; frequent roots; clear to gradual transition.
B	30 - 120+	Slightly moist; yellowish red (5YR 5/8); clay; apedal; porous; friable; common roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	786.8	600.7	17.0	17.0
Median (mm)	784.1	593.0	6.3	6.3
Sample Std. Dev. (mm)	153.97	106.23	27.75	27.75
Minimum (mm)	502.8	404.2	0.0	0.0
Maximum (mm)	1175.5	881.6	161.9	161.9
Lower quartile (mm)	663.2	527.8	0.0	0.0
Upper quartile (mm)	907.7	677.1	21.6	21.6
C.V.%	19.57	17.68	163.07	163.07
Standardized skewness	0.28	0.40	9.60	9.60
Standardized kurtosis	-0.74	-0.33	20.03	20.03

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Ixopo

Horizon[1]	A	AB	BA	B1	B2	
Depth (cm)	0-10	10-30	30-40	40-60	60-80	80-100
pH (KCl)	3.8	4.0	4.0	4.2	4.2	4.1
pH ($CaCl_2$)	4.4	4.6	4.4	4.3	4.4	4.2
pH (H_2O)	4.8	4.8	4.8	5.4	5.1	5.0
Texture						
Clay %	48	55	56	67	69	65
Silt %	25	27	18	9	8	11
Sand %	27	17	26	24	23	24
Exch. cations $cmol_c\ kg^{-1}$						
Ca	3.44	3.13	2.02	1.28	0.84	0.24
Mg	2.46	2.42	1.65	1.27	0.98	0.27
K	0.08	0.10	0.09	0.07	0.08	0.07
Na	0.29	0.40	0.29	0.37	0.26	0.29
acidity	0.82	1.68	1.55	1.64	0.98	0.74
ECEC	7.09	7.73	5.60	4.63	3.14	1.61
C %	4.84	4.63	1.32	0.77	0.66	0.63
N %	0.21	0.21	0.06	0.05	0.04	0.04
C/N	23	22	22	15	17	16
S-val/(clay)	18.01	11.00	7.23	4.46	3.13	1.34
Base sat %	88	78	72	65	69	54
LOI (430°C)	13.2	12.6	8.2	7.1	5.5	4.8

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Little Harmony Farm
Station codes	ATS0326; 0239566A
Lat.(S); Long.(E)	29°56'; 30°19'
Altitude	810m
Vegetation	*Pennisetum clandestinum* grass
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Undulating, < 2° slope
Years of data	53
Record span in years	53
Reliability index§	1.00

Pit dug 100m from farmhouse near field boundary with main road.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	Description
A	0 - 20	Moist; dark reddish brown (5YR 3/2); clay; moderate fine subangular blocky; moderately porous; hard; few concretions; common earthworms; few stones; abundant roots; gradual smooth transition.
B	20 - 115	Moist; brown (7.5YR 4/4); clay; apedal; porous; friable; few roots; gradual smooth transition.
C	115+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	891.1	651.1	64.9	49.5
Median (mm)	906.0	647.0	62.0	40.6
Sample Std. Dev. (mm)	166.84	91.03	46.41	46.28
Minimum (mm)	600.0	485.0	0.3	0.0
Maximum (mm)	1292.0	857.0	233.4	229.4
Lower quartile (mm)	776.0	577.5	33.0	14.8
Upper quartile (mm)	984.0	717.0	84.9	64.9
C.V.%	18.72	13.98	71.45	93.59
Standardized skewness	1.02	0.26	3.67	4.82
Standardized kurtosis	-0.42	-0.89	3.54	5.30

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Little Harmony

Horizon[1]	A	AB	BA	B1	B2						B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
pH (KCl)	4.2	4.0	3.9	4.0	4.0	4.0	3.9	4.2	4.2	4.2	4.2
pH ($CaCl_2$)	4.6	4.4	4.3	4.4	4.3	4.3	4.3	4.3	4.3	4.1	4.3
pH (H_2O)	5.5	5.3	5.6	5.0	5.2	5.3	5.2	5.3	5.3	5.3	5.3
Texture											
Clay %	64	65	65	67	66	67	65	65	66	66	65
Silt %	18	17	17	17	17	17	17	17	17	16	17
Sand %	18	17	18	16	17	15	17	18	17	18	18
Exch. cations $cmol_c\ kg^{-1}$											
Ca	3.63	2.72	3.10	2.94	2.87	2.59	2.67	2.50	1.80	1.31	1.20
Mg	2.96	1.95	1.87	1.57	1.59	1.49	1.57	1.41	1.30	1.16	1.18
K	0.13	0.06	0.06	0.05	0.04	0.04	0.03	0.04	0.04	0.05	0.06
Na	0.15	0.15	0.16	0.17	0.15	0.16	0.20	0.18	0.17	0.20	0.14
acidity	1.86	2.91	2.16	2.31	2.39	2.82	2.86	0.76	1.04	1.30	1.30
ECEC	8.73	7.79	7.35	7.04	7.04	7.10	7.33	4.89	4.35	4.02	3.88
C %	4.89	3.42	3.14	3.06	3.07	3.15	3.06	3.47	3.81	3.32	2.94
N %	0.30	0.19	0.19	0.19	0.17	0.17	0.12	0.19	0.19	0.12	0.15
C/N	16	18	17	16	18	19	26	18	20	28	20
S-val/(clay)	10.73	7.51	7.98	7.06	7.05	6.39	6.88	6.35	5.02	4.12	3.97
Base sat %	79	63	71	67	66	60	61	84	76	68	66
LOI (430°C)	16.0	13.7	12.2	12.9	13.1	13.4	13.0	13.5	14.1	12.7	12.5

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Richmond
Station codes	0239472W
Lat.(S); Long.(E)	29°52.3'; 30°16.4'
Altitude	884m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Undulating, flat at site
Years of data	62
Record span in years	74
Reliability index§	0.85

Samples taken from 50cm deep pit, and the remainder by auguring, in an undisturbed flat field 100m from police station.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	Description
A	0 - 40	Moist; dark reddish brown (5YR 3/3); clay; apedal; porous; friable; frequent roots; gradual transition.
B	40 - 75	Moist; strong brown (5YR 5/6); clay; apedal; porous; friable; common roots; clear transition.
C	75+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	979.8	758.6	99.6	107.1
Median (mm)	976.6	768.6	82.9	91.9
Sample Std. Dev. (mm)	263.4	168.61	92.42	93.89
Minimum (mm)	260.0	216.9	0.0	0.0
Maximum (mm)	1829.1	1189.0	481.3	488.6
Lower quartile (mm)	831.7	677.1	38.6	45.6
Upper quartile (mm)	1099.7	862.8	122.6	133.2
C.V.%	26.88	22.23	92.76	87.65
Standardized skewness	1.50	-1.26	6.24	5.98
Standardized kurtosis	2.71	2.00	6.85	6.34

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Richmond							
Horizon[1]	A1	A2		AB	BA	B1	B2	B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-75
pH (KCl)	4.3	4.3	4.5	4.6	4.7	4.7	4.7	4.7
pH ($CaCl_2$)	4.6	4.5	4.6	4.7	4.7	4.8	4.8	4.7
pH (H_2O)	5.5	5.3	5.4	5.6	5.7	5.7	5.8	5.8
Texture								
Clay %	58	63	63	63	63	65	65	65
Silt %	23	20	19	6	19	19	18	18
Sand %	20	17	18	32	17	17	17	18
Exch. cations $cmol_c\ kg^{-1}$								
Ca	1.21	0.93	0.18	0.10	0.14	0.29	0.05	0.04
Mg	1.06	0.42	0.26	0.19	0.21	0.24	0.16	0.16
K	0.22	0.18	0.14	0.09	0.06	0.04	0.04	0.04
Na	0.24	0.20	0.17	0.16	0.17	0.15	0.11	0.11
acidity	1.99	1.95	1.12	0.68	0.56	0.49	0.33	0.35
ECEC	4.72	3.68	1.87	1.22	1.14	1.21	0.69	0.70
C %	8.00	7.89	7.08	6.17	5.67	4.15	3.21	3.02
N %	0.33	0.34	0.28	0.20	0.22	0.17	0.06	0.08
C/N	24	23	25	22	26	24	54	38
S-val/(clay)	4.71	2.75	1.19	0.86	0.91	1.11	0.55	0.54
Base sat %	58	47	40	44	51	60	52	50
LOI (430°C)	22.4	22.1	21.0	19.3	19.0	17.1	15.6	15.5

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Baynesfield Estates (near main office)
Station codes	ATS0195; 0239585A
Lat.(S); Long.(E)	29°45'; 30°20'
Altitude	808m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Undulating, < 2° slope
Years of data	49
Record span in years	63
Reliability index§	0.78

Samples taken from trench under excavation, 40m from station. Bank cleared back and sampled.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	Description
A	0 - 25	Dry; dark brown (7.5YR 3/4); clay; moderate subangular blocky; porous; hard; frequent roots; many stones; gradual transition.
B	25 - 50	Slightly moist; red (2.5YR 4/8); clay; apedal; porous; friable; few roots; many stones; clear transition.
C	50+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	799.1	566.1	24.7	16.9
Median (mm)	780.8	570.6	9.6	1.9
Sample Std. Dev. (mm)	175.36	84.87	37.94	34.10
Minimum (mm)	527.8	393.9	0.0	0.0
Maximum (mm)	1570.2	828.2	220.6	202.9
Lower quartile (mm)	693.3	501.9	1.8	0.0
Upper quartile (mm)	863.4	616.3	32.6	17.6
C.V.%	21.95	14.99	153.58	201.26
Standardized skewness	5.40	0.89	9.48	11.03
Standardized kurtosis	8.66	0.72	18.25	23.55

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Baynesfield

Horizon[1]	A	AB	BA	B1	B3
Depth (cm)	0-10	10-25	25-35	35-45	45-50
pH (KCl)	5.1	5.1	5.2	5.7	5.8
pH ($CaCl_2$)	5.4	5.6	5.7	5.9	6.1
pH (H_2O)	5.8	6.0	5.7	5.7	6.2
Texture					
Clay %	55	59	61	73	56
Silt %	13	11	10	7	9
Sand %	32	30	29	20	35
Exch. cations $cmol_c\ kg^{-1}$					
Ca	9.22	7.20	4.22	3.15	3.46
Mg	3.20	3.14	2.45	2.57	2.44
K	0.79	0.61	0.88	2.55	1.64
Na	0.42	0.38	0.26	0.37	0.29
acidity	0.06	0.26	0.19	0.17	0.20
ECEC	13.69	11.59	8.00	8.81	8.03
C %	2.44	2.32	1.29	0.41	0.38
N %	0.13	0.12	0.07	0.03	0.06
C/N	19	19	18	14	6
S-val/(clay)	24.78	19.20	12.80	11.84	13.98
Base sat %	100	98	98	98	98
LOI (430°C)	9.8	9.4	8.2	7.3	7.4

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Cramond, Albert Falls - farm of D. Mackenzie
Station codes	0269774A; ATS0241
Lat.(S); Long.(E)	29°24'; 30°26'
Altitude	762m
Vegetation	*Aristida-Eragrostis* grassland
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Gentle; less than 2°
Years of data	69
Record span in years	71
Reliability index§	0.97

Samples taken from road cutting 100m from farmstead. Bank cleared back and sampled.

Soil -	Ma1100 silty loam
Form -	Magwa
Series -	Connemara

Horizon	depth (cm)	Description
A	0 - 20	Slightly moist; dark yellowish brown (10YR 4/4); silty loam; apedal; porous; friable; frequent roots; gradual transition.
B	20 - 80	Slightly moist; yellowish brown (10YR 5/6); clay; apedal; porous; friable; frequent roots; gradual transition.
C	80+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	967.8	760.3	143.5	137.0
Median (mm)	943.0	752.0	120.8	116.7
Sample Std. Dev. (mm)	193.09	133.65	86.48	86.29
Minimum (mm)	590.6	491.7	13.2	13.1
Maximum (mm)	1418.1	1074.6	386.8	383.7
Lower quartile (mm)	824.5	672.6	76.9	69.9
Upper quartile (mm)	1100.0	847.6	199.1	192.9
C.V.%	19.95	17.58	60.26	63.00
Standardized skewness	1.19	0.34	2.69	2.83
Standardized kurtosis	-0.57	-0.94	0.09	0.22

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Cramond			
Horizon[1]	AB	BA	B1	B2
Depth (cm)	0-20	20-40	40-60	60-80
pH (KCl)	4.3	4.1	4.0	3.9
pH ($CaCl_2$)	5.3	4.5	4.5	4.3
pH (H_2O)	5.5	4.9	4.9	5.2
Texture				
Clay %	37	39	57	56
Silt %	30	20	21	19
Sand %	33	39	22	25
Exch. cations $cmol_c\ kg^{-1}$				
Ca	4.97	2.30	1.55	2.27
Mg	3.54	1.88	1.48	2.93
K	0.59	0.15	0.13	0.14
Na	0.27	0.22	0.21	0.18
acidity	0.63	1.56	2.62	1.16
ECEC	10.00	6.11	5.99	6.68
C %	3.00	2.06	1.48	0.89
N %	0.20	nd	0.13	0.04
C/N	15	nd	11	22
S-val/(clay)	25.32	11.67	5.91	9.86
Base sat %	94	74	56	83
LOI (430°C)	8.1	7.7	7.2	4.4

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Hawkestone Farm, Howick
Station codes	0269532A; ATS0314
Lat.(S); Long.(E)	29°22'; 30°18'
Altitude	1075m
Vegetation	*Pennisetum clandestinum* grass
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Slope 5°
Years of data	67
Record span in years	69
Reliability index§	0.97

Samples taken from pit dug 25m from house and rainfall gauge.

Soil - Ia1200 silty loam
Form - Inanda
Series - Highlands

Horizon	depth (cm)	Description
A	0 - 15	Moist; strong brown (7.5YR 4/6); silty loam; weak subangular blocky; porous; friable; frequent roots; gradual transition.
B	15 - 70	Moist; reddish yellow (5YR 6/8); clay; apedal; porous; friable; common roots; clear transition.
C	70+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1204.4	984.5	328.5	320.8
Median (mm)	1147.3	955.8	301.1	290.8
Sample Std. Dev. (mm)	223.33	157.19	131.88	137.00
Minimum (mm)	839.7	691.0	116.8	104.2
Maximum (mm)	1998.0	1406.0	6604	676.1
Lower quartile (mm)	1048.3	870.3	218.7	208.3
Upper quartile (mm)	1331.9	1105.3	430.4	427.8
C.V.%	18.54	15.97	40.15	42.71
Standardized skewness	3.19	1.80	1.87	2.06
Standardized kurtosis	2.26	-0.04	-0.73	-0.54

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Hawkestone

Horizon[1]	AB	BA	B1	B2	B3
Depth (cm)	0-15	15-30	30-50	50-60	60-70
pH (KCl)	4.1	4.3	4.5	4.0	4.3
pH ($CaCl_2$)	4.5	4.8	4.3	4.4	4.4
pH (H_2O)	5.1	5.1	4.5	4.8	5.2
Texture					
Clay %	28	66	55	60	55
Silt %	35	15	11	8	16
Sand %	37	19	34	32	29
Exch. cations $cmol_c\ kg^{-1}$					
Ca	7.23	2.74	0.52	0.91	1.54
Mg	4.18	0.78	0.28	0.25	0.45
K	0.55	1.58	1.21	0.93	0.89
Na	0.18	0.26	0.15	0.16	0.16
acidity	2.35	0.46	0.41	0.96	0.55
ECEC	14.49	5.82	2.57	3.21	3.59
C %	6.12	2.16	1.40	0.72	0.24
N %	0.38	0.15	0.08	0.05	0.07
C/N	16	14	18	14	3
S-val/(clay)	43.36	8.12	3.93	3.75	5.53
Base sat %	84	92	84	70	85
LOI (430°C)	17.0	11.1	10.7	9.2	5.6

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Rambleholm farm, Albert Falls
Station codes	0269716W; 269686
Lat.(S); Long.(E)	29°26.3'; 30°22.8'
Altitude	671m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Ecca group shale, Pietermaritzburg formation, with dolerite boulders in vicinity
Topography	Gentle, less than 2°
Years of data	32
Record span in years	46
Reliability index§	0.70

Samples taken from road cutting 50m from farmhouse. Bank cleared back and sampled.

Soil - Ma1100 silty loam
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	Description
A	0 - 10	Moist; dark brown (7.5YR 3/4); clay; moderate fine subangular blocky; porous; friable; frequent roots; gradual transition.
B	10 - 60	Moist; brown (10YR 4/3); clay; apedal; porous; friable; few roots; gradual transition.
C	60+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	794.1	585.1	121.8	103.4
Median (mm)	781.9	588.7	106.9	77.0
Sample Std. Dev. (mm)	171.44	105.20	66.24	68.74
Minimum (mm)	432.3	356.9	3.8	0.0
Maximum (mm)	1138.9	808.2	256.8	246.4
Lower quartile (mm)	678.9	517.8	73.8	54.5
Upper quartile (mm)	916.9	657.5	176.0	165.6
C.V.%	21.59	17.98	54.38	66.49
Standardized skewness	0.22	-0.34	1.07	1.50
Standardized kurtosis	-0.75	-0.80	-0.96	-1.04

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Rambleholm			
Horizon[1]	AB	BA	B1	B2
Depth (cm)	0-10	10-20	20-40	40-60
pH (KCl)	5.3	4.5	4.0	4.5
pH ($CaCl_2$)	5.9	4.8	4.4	4.6
pH (H_2O)	6.0	5.2	5.0	5.2
Texture				
Clay %	51	43	45	48
Silt %	20	17	17	12
Sand %	29	40	38	40
Exch. cations $cmol_c\ kg^{-1}$				
Ca	4.32	3.02	2.19	2.14
Mg	1.70	1.87	2.14	1.56
K	0.13	0.15	0.18	0.12
Na	0.11	0.20	0.41	0.22
acidity	0.24	1.55	2.04	1.48
ECEC	6.50	6.79	6.97	5.52
C %	3.26	2.19	1.98	1.87
N %	0.21	0.15	0.13	0.13
C/N	16	15	15	14
S-val/(clay)	12.27	12.19	10.93	8.42
Base sat %	96	77	71	73
LOI (430°C)	8.8	6.4	6.0	4.8

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Weston College, Mooi River
Station codes	0269043A; ATS0201
Lat.(S); Long.(E)	29° 13'; 30° 02'
Altitude	1371m
Vegetation	*Themeda-Hyperrhenia* grassland
Parent material	Natal group sandstone, with dolerite in vicinity
Topography	Crest of small hillock
Years of data	62
Record span in years	62
Reliability index§	1.00

Samples taken from large road-cutting adjacent to school. Bank cleared back and sampled.

Soil - Sd1110 silty loam
Form - Shortlands
Series - Tongaat

Horizon	depth (cm)	Description
A	0 - 30	Slightly moist; dark greyish brown (10YR 4/2); clay loam; friable getting firmer with depth; frequent roots; clear transition.
B	30 - 100+	Moist; reddish brown (5YR 5/4); clay; subangular blocky; moderately porous; friable; slight evidence of mottling with depth; frequent roots; frequent concretions.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	714.9	558.3	40.0	34.6
Median (mm)	674.6	541.6	30.2	27.0
Sample Std. Dev. (mm)	154.4	106.2	40.21	38.60
Minimum (mm)	403.1	325.6	0.0	0.0
Maximum (mm)	1113.4	817.5	173.3	165.2
Lower quartile (mm)	604.9	482.9	9.5	7.0
Upper quartile (mm)	812.0	620.3	48.9	40.0
C.V.%	21.59	19.02	100.60	111.50
Standardized skewness	2.22	1.37	5.18	5.82
Standardized kurtosis	0.63	-0.08	4.09	5.05

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Weston

Horizon[1]	A1	A2	AB	BA	B1	B2		
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
pH (KCl)	4.6	4.8	5.1	4.6	4.3	4.4	4.6	4.7
pH ($CaCl_2$)	5.3	5.6	5.9	5.2	4.8	4.9	5.0	5.1
pH (H_2O)	6.0	6.0	6.1	6.0	5.7	5.8	5.8	6.0
Texture								
Clay %	37	36	38	40	42	44	50	54
Silt %	15	14	14	14	13	13	14	13
Sand %	49	50	48	47	44	43	36	33
Exch. cations $cmol_c\ kg^{-1}$								
Ca	4.48	4.12	3.68	2.12	2.02	1.89	2.13	2.14
Mg	1.20	1.28	1.22	1.34	2.26	2.73	2.65	3.01
K	0.62	0.58	0.50	0.54	0.48	0.37	0.25	0.25
Na	0.25	0.25	0.23	0.17	0.19	0.22	0.18	0.23
acidity	0.12	0.09	0.10	0.10	0.26	0.12	0.11	0.10
ECEC	6.67	6.32	5.73	4.27	5.21	5.33	5.32	5.73
C %	2.09	1.99	1.61	1.47	1.11	0.69	0.49	0.45
N %	0.12	0.10	0.10	0.07	0.07	0.05	0.05	0.06
C/N	17	20	16	21	16	14	10	8
S-val/(clay)	17.70	17.31	14.82	10.43	11.79	11.84	10.42	10.43
Base sat %	98	99	98	98	95	98	97	98
LOI (430°C)	6.1	6.0	5.7	5.7	5.2	3.6	4.4	5.1

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Westfield farm, Balgowan, R.W.Johnston
Station codes	0269111A; ATS0322
Lat.(S); Long.(E)	29°21'; 30°04'
Altitude	1375m
Vegetation	*Pennisetum clandestinum* grass
Parent material	Dolerite with Beaufort group shale, Estcourt formation
Topography	Gentle slope 2°
Years of data	42
Record span in years	43
Reliability index§	0.98

Samples taken from pit dug near plain trees, 20m from farmhouse.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	Description
A	0 - 15	Moist; yellowish red (5YR 4/6); clay; apedal; porous; friable; abundant roots; small earthworms; gradual transition.
B	15 - 120+	Moist; red (2.5YR 4/6); clay; apedal; porous; friable; frequent roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1014.5	743.4	229.0	247.7
Median (mm)	1014.4	739.7	235.1	255.4
Sample Std. Dev. (mm)	179.00	103.96	81.83	94.65
Minimum (mm)	673.0	542.2	85.0	74.7
Maximum (mm)	1428.2	950.3	397.8	447.6
Lower quartile (mm)	920.8	668.8	168.7	182.6
Upper quartile (mm)	1148.1	805.9	268.3	287.9
C.V.%	17.64	13.99	35.73	38.22
Standardized skewness	0.30	-0.43	0.54	0.62
Standardized kurtosis	0.08	-0.78	-0.62	-0.56

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Westfield

Horizon[1]	A	AB	BA	B1	B2					
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-100	100-120
pH (KCl)	4.7	4.7	4.8	5.0	5.2	5.4	5.5	5.6	5.7	5.6
pH ($CaCl_2$)	5.1	5.1	5.1	5.3	5.5	5.6	5.7	5.8	5.9	5.9
pH (H_2O)	5.9	5.9	6.0	5.9	6.1	6.1	6.3	6.2	6.5	6.6
Texture										
Clay %	53	62	62	64	66	66	67	67	67	67
Silt %	15	17	15	15	12	12	12	12	12	13
Sand %	32	21	23	21	22	22	21	21	21	20
Exch. cations $cmol_c\ kg^{-1}$										
Ca	6.73	4.69	2.83	1.99	2.21	2.67	2.23	2.17	2.31	2.43
Mg	2.32	1.38	0.91	0.78	0.87	1.11	1.14	1.45	1.85	2.27
K	0.79	0.16	0.06	0.05	0.05	0.05	0.04	0.05	0.06	0.06
Na	0.11	0.13	0.12	0.12	0.14	0.16	0.17	0.21	0.23	0.21
acidity	0.20	0.25	0.20	0.15	0.10	0.15	0.10	0.10	0.10	0.12
ECEC	10.15	6.61	4.12	3.09	3.37	4.14	3.68	3.98	4.55	5.09
C %	4.29	3.23	2.78	1.49	1.14	0.92	064	0.40	0.34	0.25
N %	0.29	0.22	0.22	0.11	0.08	0.05	0.05	0.05	0.05	0.05
C/N	15	15	13	14	14	18	13	8	7	5
S-val/(clay)	18.77	10.26	6.32	4.59	4.95	6.05	5.34	5.79	6.64	7.42
Base sat %	98	96	95	95	97	96	97	97	98	98
LOI (430°C)	14.2	13.8	14.5	12.9	12.8	12.5	11.3	11.4	11.1	10.6

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Reid of Carpe Diem, Balgowan (formally L C Knight)
Station codes	0269114A; ATS0332
Lat.(S); Long.(E)	29°24'; 30°04'
Altitude	1400m
Vegetation	*Themeda-Hyperrhenia* grassland
Parent material	Dolerite
Topography	Gentle, less than 5°
Years of data	52
Record span in years	53
Reliability index§	0.98

Pit dug to 50cm. Deeper samples taken by auger. Site on gentle slope just below house.

Soil - Ia1200 clay
Form - Inanda
Series - Highlands

<u>Horizon</u>	<u>depth (cm)</u>	<u>Description</u>
A	0 - 15	Moist; brown (7.5YR 4/4); clay; apedal; porous; friable; frequent roots; gradual transition.
B	15 - 120+	Moist; yellowish brown (5YR 4/6); clay; apedal; porous; friable; common roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1026.3	798.1	250.5	280.94
Median (mm)	1005.1	792.8	249.7	279.4
Sample Std. Dev. (mm)	169.99	114.99	84.51	102.99
Minimum (mm)	657.1	506.7	103.1	113.9
Maximum (mm)	1481.4	1087.2	468.5	557.1
Lower quartile (mm)	927.2	733.3	206.0	225.1
Upper quartile (mm)	1107.1	856.1	286.2	325.8
C.V.%	16.56	14.41	33.73	36.66
Standardized skewness	1.40	0.90	1.69	2.14
Standardized kurtosis	0.90	1.26	0.78	1.24

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Knight					
Horizon[1]	AB	BA	B1	B2		
Depth (cm)	0-15	15-25	25-35	35-60	60-80	80-100
pH (KCl)	4.4	4.2	4.1	4.5	4.6	4.8
pH ($CaCl_2$)	5.0	4.4	4.2	4.7	4.7	5.0
pH (H_2O)	5.2	4.9	4.6	5.2	5.6	5.9
Texture						
Clay %	44	48	61	68	66	61
Silt %	24	12	7	6	8	10
Sand %	32	40	32	26	26	29
Exch. cations $cmol_c\ kg^{-1}$						
Ca	3.09	2.12	0.52	0.80	1.16	0.71
Mg	1.49	0.84	0.26	0.35	0.45	0.27
K	0.67	0.32	0.09	0.10	0.11	0.07
Na	0.17	0.16	0.14	0.13	0.09	0.11
acidity	0.89	1.29	2.22	1.86	0.45	0.04
ECEC	6.31	4.73	3.23	3.24	2.26	1.20
C %	4.26	2.66	1.52	1.64	1.65	0.98
N %	0.26	0.13	0.09	0.08	0.07	0.03
C/N	16	20	17	21	24	31
S-val/(clay)	12.32	7.17	1.66	2.03	2.74	1.90
Base sat %	86	73	31	43	80	97
LOI (430°C)	14.2	10.2	8.1	8.0	7.6	7.6

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Nutfield farm, Lidgetton, J.Lister
Station codes	0269147A; ATS0222
Lat.(S); Long.(E)	29°27'; 30°05'
Altitude	1200m
Vegetation	*Pennisetum clandestinum* grass
Parent material	Ecca group shale, Volksrust formation, with dolerite in vicinity
Topography	5°
Years of data	35
Record span in years	37
Reliability index§	0.95

Samples taken from pit, 50m from farmhouse, adjacent to field.

Soil - Kp1100 clay
Form - Kranskop
Series - Fordoun

Horizon	depth (cm)	Description
A	0 - 20	Moist; dark yellowish brown (10YR 3/4); clay; apedal; porous; friable; frequent roots; gradual transition.
B1	20 - 55	Moist; strong brown (7.5YR 5/6); clay; friable; apedal; frequent roots; clear transition.
B2	55 - 120	Moist; red (2.5YR 4/8); clay; apedal; porous; friable; gradual transition.
C	120+	Pink shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1042.7	791.0	259.4	260.4
Median (mm)	1000.7	778.5	243.3	243.1
Sample Std. Dev. (mm)	173.01	91.28	83.19	88.89
Minimum (mm)	718.9	582.1	134.7	125.8
Maximum (mm)	1664.5	1040.7	485.1	500.9
Lower quartile (mm)	928.8	733.9	198.0	193.3
Upper quartile (mm)	1103.2	852.9	335.3	338.3
C.V.%	16.59	11.54	32.07	34.14
Standardized skewness	3.31	1.20	1.75	1.77
Standardized kurtosis	4.30	0.73	0.02	-0.01

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Nutfield									
Horizon[1]	A1	AB	BA	B1	B2					B3
Depth (cm)	0-10	10-20	20-30	30-45	45-60	60-80	80-90	90-100	100-120	120-130
pH (KCl)	4.1	4.2	4.3	4.3	4.3	4.3	4.3	4.2	4.3	4.2
pH ($CaCl_2$)	4.6	4.5	4.5	4.5	4.5	4.4	4.4	4.4	4.4	4.4
pH (H_2O)	5.4	5.4	5.4	5.5	5.3	5.5	5.2	5.0	5.1	4.9
Texture										
Clay %	58	60	61	61	61	62	62	61	60	61
Silt %	14	15	13	13	14	1	17	17	17	18
Sand %	28	25	26	26	26	25	22	22	23	21
Exch. cations $cmol_c\ kg^{-1}$										
Ca	4.31	2.16	0.80	0.46	0.45	0.42	0.35	0.42	0.54	0.47
Mg	2.88	1.23	0.51	0.29	0.28	0.26	0.21	0.31	0.47	0.41
K	0.55	0.32	0.17	0.15	0.11	0.10	0.09	0.09	0.10	0.09
Na	0.12	0.14	0.16	0.12	0.16	0.13	0.09	0.09	0.10	0.13
acidity	0.93	1.59	1.37	1.11	1.11	1.14	1.43	1.38	1.13	1.43
ECEC	8.79	5.44	3.01	2.13	2.11	2.05	2.17	2.29	2.34	2.53
C %	8.54	6.54	4.21	2.99	2.41	1.81	1.11	0.42	0.32	0.25
N %	0.61	0.61	0.27	0.22	0.16	0.19	0.11	0.08	0.05	0.05
C/N	14	11	16	14	15	10	10	5	6	5
S-val/(clay)	13.55	6.42	2.69	1.67	1.64	1.47	1.19	1.49	2.02	1.80
Base sat %	89	71	54	48	47	44	34	40	52	43
LOI (430°C)	22.5	18.5	15.3	13.5	13.5	12.5	11.0	9.4	8.5	7.0

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Glen Eland (NTE estate)
Station codes	0270722W; 270752
Lat.(S); Long.(E)	29°02.2'; 30°56'
Altitude	1050m
Vegetation	Sparse *Themeda-Hyperrhenia* grassland
Parent material	Natal group sandstone
Topography	top of ridge
Years of data	55
Record span in years	58
Reliability index§	0.95

Samples taken from exposed road cutting 100m from farmhouse. Bank cleared back and sampled.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	Description
A	0 - 30	Moist; dark brown (10YR 3/3); clay; apedal; porous; friable; few roots; gradual transition.
B	30 - 100+	Moist; dark yellowish brown (10YR 4/4); clay; apedal; porous; friable; few roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	956.9	704.0	72.0	72.0
Median (mm)	966.9	715.9	64.8	64.8
Sample Std. Dev. (mm)	242.97	139.59	55.00	55.00
Minimum (mm)	499.1	348.0	0.0	0.0
Maximum (mm)	1854.0	983.4	268.3	268.3
Lower quartile (mm)	764.8	604.7	32.84	32.84
Upper quartile (mm)	1110.4	797.8	102.18	102.18
C.V.%	25.39	19.83	76.35	76.35
Standardized skewness	1.96	-1.34	3.77	3.77
Standardized kurtosis	3.09	-0.44	3.29	3.29

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Glen Eland					
Horizon[1]	A	AB	BA	B1	B2	B3
Depth (cm)	0-15	15-30	30-45	45-55	55-75	75-90
pH (KCl)	3.8	3.7	4.0	4.1	4.0	4.1
pH ($CaCl_2$)	3.8	3.7	4.1	4.1	4.2	4.1
pH (H_2O)	4.3	4.5	4.9	4.8	4.8	5.0
Texture						
Clay %	59	57	60	66	68	68
Silt %	16	15	10	6	6	4
Sand %	25	28	30	28	26	28
Exch. cations $cmol_c\ kg^{-1}$						
Ca	0.60	0.45	0.55	0.51	0.48	0.37
Mg	0.10	0.14	0.10	0.09	0.12	0.19
K	0.14	0.11	0.12	0.09	0.08	0.11
Na	0.17	0.13	0.15	0.21	0.16	0.09
acidity	4.54	1.52	1.66	1.87	1.66	0.10
ECEC	5.55	2.35	2.58	2.77	2.50	0.86
C %	4.88	5.25	4.54	3.06	2.63	2.71
N %	0.25	0.29	0.19	0.10	0.12	0.10
C/N	20	18	24	31	22	27
S-val/(clay)	1.71	1.46	1.53	1.36	1.24	1.12
Base sat %	18	35	36	32	34	88
LOI (430°C)	16.0	17.5	15.3	12.5	12.3	11.2

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Linklater (now Dougvale, D. Cross)
Station codes	0302687W; 302718
Lat. and Long	28°57.7'; 30°54.4'
Altitude	1097m
Vegetation	None, cleared ground
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Flat
Years of data	38
Record span in years	42
Reliability index§	0.90

Samples taken pit excavated 10m from rainguage.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

<u>Horizon</u>	<u>depth (cm)</u>	<u>Description</u>
A	0 - 40	Moist; dark greyish brown (10YR 4/2); clay; apedal; porous; friable; few roots; clear transition.
B	40 - 80	Moist; yellow (10YR 7/8); clay; apedal; porous; friable; few roots; gradual transition.
C	80+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	903.1	703.4	61.2	61.2
Median (mm)	870.1	687.6	48.3	48.3
Sample Std. Dev. (mm)	193.98	101.32	51.47	51.47
Minimum (mm)	526.0	471.4	0.0	0.0
Maximum (mm)	1753.6	994.6	269.2	269.2
Lower quartile (mm)	797.4	642.3	31.2	31.2
Upper quartile (mm)	998.7	791.4	83.3	83.3
C.V.%	21.48	14.40	84.12	84.12
Standardized skewness	5.05	1.08	5.28	5.28
Standardized kurtosis	10.83	0.72	7.61	7.61

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Linklater			
Horizon[1]	A	AB	B1	B2
Depth (cm)	0-30	30-45	45-55	55-70
pH (KCl)	3.9	4.0	4.1	4.0
pH ($CaCl_2$)	4.3	4.2	4.3	4.1
pH (H_2O)	4.8	4.7	4.8	5.0
Texture				
Clay %	55	53	56	69
Silt %	9	10	14	9
Sand %	36	37	30	22
Exch. cations $cmol_c\ kg^{-1}$				
Ca	2.25	1.48	1.26	0.72
Mg	0.61	0.55	0.47	0.51
K	0.26	0.22	0.22	0.23
Na	0.17	0.18	0.16	0.10
acidity	2.57	2.02	1.87	0.11
ECEC	5.86	4.45	3.98	1.67
C %	3.64	2.12	0.57	0.82
N %	0.24	0.16	0.07	0.06
C/N	15	13	8	14
S-val/(clay)	5.98	4.58	3.77	2.26
Base sat %	56	55	53	93
LOI (430°C)	9.8	8.2	4.5	6.9

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Kranskop
Station codes	0302628W
Lat. and Long	28°58'; 30°51'
Altitude	1173m
Vegetation	None, cleared ground
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Flat
Years of data	51
Record span in years	58
Reliability index§	0.88

Sample taken from pit dug for a building construction adjacent to police station.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	Description
A	0 - 20	Dry; strong brown (7.5YR 4/6); clay; moderate subangular blocky; porous; friable; common roots; common small concretions; gradual transition.
B	20 - 120+	Slightly moist; red (2.5YR 4/8); clay; apedal; porous; friable; common concretions; common roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	869.8	634.7	49.7	54.1
Median (mm)	874.9	650.0	40.9	44.5
Sample Std. Dev. (mm)	194.67	107.78	41.85	42.49
Minimum (mm)	513.1	400.8	0.0	0.0
Maximum (mm)	1516.5	861.1	237.82	242.3
Lower quartile (mm)	714.6	560.2	21.3	27.7
Upper quartile (mm)	970.5	722.6	64.1	68.6
C.V.%	22.38	16.98	84.23	78.51
Standardized skewness	2.21	-0.79	6.20	5.80
Standardized kurtosis	2.47	-0.96	10.06	9.24

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Kranskop			
Horizon[1]	AB	BA	B1	B2
Depth (cm)	0-20	20-40	40-65	65-80
pH (KCl)	4.1	4.4	4.2	4.6
pH ($CaCl_2$)	4.5	4.6	4.2	4.8
pH (H_2O)	5.1	5.5	4.5	5.4
Texture				
Clay %	60	55	65	69
Silt %	11	21	10	9
Sand %	30	24	25	22
Exch. cations $cmol_c\ kg^{-1}$				
Ca	1.20	1.18	0.18	1.25
Mg	1.55	0.55	0.52	1.65
K	0.13	0.14	0.09	0.22
Na	0.21	0.09	0.19	0.23
acidity	2.15	0.07	1.42	1.12
ECEC	5.24	2.03	2.40	4.47
C %	2.58	3.18	0.73	0.27
N %	0.13	0.13	0.08	nd
C/N	20	24	9	nd
S-val/(clay)	5.15	3.56	1.51	4.86
Base sat %	59	97	41	75
LOI (430°C)	9.3	15.9	6.1	3.4

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Inadi
Station codes	0302320W
Lat. and Long	28°50.5'; 30°41'
Altitude	863m
Vegetation	*Acacia* thornveld
Parent material	Dolerite
Topography	Gentle slope
Years of data	50
Record span in years	70
Reliability index§	0.71

Samples taken from road cutting near old house and store. Bank cleared back and sampled.

Soil - Sd2220 sandy clay loam
Form - Shortlands
Series - Zebediela

Horizon	depth (cm)	Description
A	0 - 5	Dry; dark yellowish brown (10YR 4/4); sandy clay loam; apedal; porous; friable; few roots; common stones; gradual transition.
B	5 - 120+	Dry; dusky red (2.5YR 3/2); sandy clay; strong medium subangular blocky; porous; firm; few roots; common stones.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	617.8	361.1	28.6	14.3
Median (mm)	598.2	364.1	22.1	6.4
Sample Std. Dev. (mm)	148.04	64.52	25.67	21.50
Minimum (mm)	291.5	207.7	0.0	0.0
Maximum (mm)	1010.5	529.8	125.7	104.1
Lower quartile (mm)	526.4	326.6	8.8	0.0
Upper quartile (mm)	716.1	398.5	39.9	20.0
C.V.%	23.96	17.87	89.73	150.61
Standardized skewness	1.66	0.03	5.34	8.69
Standardized kurtosis	0.80	-0.03	5.46	12.70

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Inadi			
Horizon[1]	AB	BA	B1	B2
Depth (cm)	0-5	5-25	25-45	45-60
pH (KCl)	5.9	6.2	6.5	6.8
pH ($CaCl_2$)	6.0	6.3	6.5	6.8
pH (H_2O)	6.1	6.3	6.5	6.9
Texture				
Clay %	27	33	35	43
Silt %	8	10	12	9
Sand %	65	57	53	48
Exch. cations $cmol_c\ kg^{-1}$				
Ca	8.48	15.81	24.92	26.80
Mg	4.00	6.43	12.69	13.20
K	0.66	1.42	2.56	2.84
Na	0.20	0.23	0.22	0.23
acidity	0.19	0.20	0.17	0.05
ECEC	13.53	24.09	40.56	43.12
C %	1.90	1.96	2.68	1.82
N %	0.16	0.16	0.23	0.10
C/N	12	12	12	18
S-val/(clay)	49.41	72.39	115.40	100.16
Base sat %	99	99	100	100
LOI (430°C)	3.9	4.0	6.1	4.3

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	The Gem (P. Van Rooyen)
Station codes	0270243A; ATS0282
Lat. and Long	29°03'; 30°39'
Altitude	1010m
Vegetation	Recently burnt *Themeda-Hyperrhenia* grassland
Parent material	Ecca group shale, Pietermaritzburg formation, with dolerite in vicinity
Topography	Gentle slope, less than 3°
Years of data	40
Record span in years	42
Reliability index§	0.95

Sample taken from 50cm deep pit dug near farmhouse. Deeper samples obtained by auguring.

Soil - Ia1200 clay
Form - Inanda
Series - Highlands

Horizon	depth (cm)	Description
A	0 - 10	Slightly moist; dark brown (7.5YR 3/4); clay; structureless; porous; friable; common roots; gradual transition.
B	10 - 50	Slightly moist; red (2.5YR 4/8); clay; apedal; porous; friable; few roots; gradual transition.
C	50+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	801.2	603.5	121.3	119.5
Median (mm)	767.0	584.2	116.2	107.7
Sample Std. Dev. (mm)	178.3	97.73	59.66	76.2
Minimum (mm)	486.9	402.2	27.8	9.7
Maximum (mm)	1244.1	843.9	257.0	311.2
Lower quartile (mm)	657.6	527.7	81.9	65.9
Upper quartile (mm)	918.2	667.9	149.5	153.9
C.V.%	22.25	16.19	49.18	63.74
Standardized skewness	1.70	1.81	1.95	2.63
Standardized kurtosis	0.06	0.33	0.05	0.88

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : The Gem

Horizon[1]	AB	BA		B1	B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50
pH (KCl)	3.7	3.8	3.8	3.8	3.7
pH ($CaCl_2$)	3.9	3.9	4.0	4.1	4.2
pH (H_2O)	4.5	4.4	4.6	4.9	4.4
Texture					
Clay %	52	52	52	79	81
Silt %	13	12	13	14	12
Sand %	35	35	35	7	7
Exch. cations $cmol_c\ kg^{-1}$					
Ca	0.28	0.23	0.16	0.26	0.22
Mg	0.28	0.21	0.21	0.75	1.05
K	0.34	0.29	0.28	0.28	0.27
Na	0.14	0.16	0.16	0.15	0.13
acidity	2.94	2.62	2.50	1.90	1.14
ECEC	3.98	3.51	3.31	3.34	2.81
C %	4.67	4.22	3.86	1.87	0.95
N %	0.29	0.25	0.24	0.11	0.09
C/N	16	17	16	17	11
S-val/(clay)	2.00	1.71	1.56	1.82	2.06
Base sat %	26	25	24	43	59
LOI (430°C)	12.4	11.6	11.1	10.9	9.5

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Boscombe (NTE estate)
Station codes	0270544W
Lat. and Long	29°03.9'; 30°48.8'
Altitude	1140m
Vegetation	*Aristida* grassland
Parent material	Ecca group shale, Pietermaritzburg formation
Topography	Gently undulating 3° slope
Years of data	56
Record span in years	62
Reliability index§	0.90

Samples taken from a road cutting 40m from rainguage at the main estate office. Bank cleared back and sampled.

Soil - Ma1200 silty clay loam
Form - Magwa
Series - Connemara

Horizon	depth (cm)	Description
A	0 - 35	Slightly moist; dark yellowish brown (10YR 4/4); silty clay loam; apedal; porous; friable; common roots; gradual transition.
B	35 - 120+	Moist; strong brown (7.5YR 5/6); clay; apedal; porous; friable; common roots.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1078.7	904.5	191.2	197.9
Median (mm)	1042.4	894.5	175.2	182.3
Sample Std. Dev. (mm)	207.45	158.8	116.28	116.21
Minimum (mm)	702.5	588.9	5.81	9.6
Maximum (mm)	1671.4	1346.7	554.5	557.1
Lower quartile (mm)	927.0	787.4	109.1	115.7
Upper quartile (mm)	1185.5	997.3	256.5	262.9
C.V.%	19.23	17.56	60.81	58.72
Standardized skewness	1.66	0.83	2.81	2.64
Standardized kurtosis	0.52	0.16	2.18	2.00

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Boscombe			
Horizon[1]	A	AB	B1	B3
Depth (cm)	0-20	20-40	40-60	60-80
pH (KCl)	4.4	4.3	4.7	4.9
pH ($CaCl_2$)	4.6	4.4	4.4	5.0
pH (H_2O)	5.0	5.3	4.8	5.3
Texture				
Clay %	35	38	49	56
Silt %	23	20	17	8
Sand %	42	42	34	36
Exch. cations $cmol_c\ kg^{-1}$				
Ca	0.62	0.29	0.10	0.15
Mg	0.35	0.20	0.05	0.08
K	0.20	0.14	0.07	0.12
Na	0.21	0.19	0.20	0.12
acidity	1.37	1.06	0.40	0.27
ECEC	2.75	1.83	0.82	0.74
C %	5.35	4.57	2.04	1.12
N %	0.24	0.20	0.08	0.06
C/N	22	23	26	19
S-val/(clay)	3.94	2.16	0.86	0.84
Base sat %	50	45	51	64
LOI (430°C)	16.8	14.8	12.1	10.7

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Eston
Station codes	0240022W
Lat.(S); Long.(E)	29°52.2'; 30°30.6'
Altitude	792m
Vegetation	*Hyperrhenia* grassland
Parent material	Dolerite and Ecca group shale, Pietermaritzburg formation
Topography	crest
Years of data	57
Record span in years	68
Reliability index§	0.84

Pit dug 50m from grid reference, near side of road.

Soil - Sd1220 clay
Form - Shortlands
Series - Sebati

Horizon	depth (cm)	description
A	0 - 30	Moist; dark reddish brown (2.5YR 2.5/4); clay; moderate fine subangular blocky; porous; friable; common roots; gradual transition.
B	30 - 60	Moist; dark red (2.5YR 3/6); clay; strong fine subangular blocky; moderately porous; firm; few roots; clear transition.
C	60+	Dolerite saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	711.4	510.0	15.6	5.6
Median (mm)	693.8	512.4	5.9	0.0
Sample Std. Dev. (mm)	141.32	77.47	25.65	20.04
Minimum (mm)	454.2	342.0	0.0	0.0
Maximum (mm)	1317.1	792.8	181.5	155.7
Lower quartile (mm)	632.8	462.4	0.6	0.0
Upper quartile (mm)	785.3	556.1	23.4	4.7
C.V.%	19.86	15.19	164.66	355.54
Standardized skewness	4.37	2.24	14.68	22.28
Standardized kurtosis	6.88	3.61	44.02	82.27

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Eston					
Horizon[1]	A1	A2	AB	B1	B2	B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60
pH (KCl)	4.2	4.1	4.3	4.8	4.9	4.8
pH ($CaCl_2$)	4.7	4.5	4.8	5.1	5.2	5.1
pH (H_2O)	5.5	5.4	5.5	5.8	6.0	5.7
Texture						
Clay %	65	70	72	91	92	71
Silt %	16	15	11	6	4	25
Sand %	19	15	17	3	4	4
Exch. cations $cmol_c\ kg^{-1}$						
Ca	5.66	3.73	4.04	4.20	2.96	2.60
Mg	4.83	4.51	4.69	5.35	5.04	4.92
K	0.22	0.49	0.36	0.18	0.12	0.13
Na	0.30	0.28	0.27	0.30	0.42	0.39
acidity	0.77	1.36	0.63	0.18	0.16	0.21
ECEC	11.78	10.37	9.99	10.21	8.70	8.25
C %	5.02	4.37	3.27	1.41	0.73	0.84
N %	0.23	0.19	0.14	0.09	0.03	0.02
C/N	22	23	24	15	27	40
S-val/(clay)	16.94	12.87	13.00	11.02	9.28	11.32
Base sat %	93	87	94	98	98	97
LOI (430°C)	13.3	12.7	10.6	9.4	7.5	7.5

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[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Qudeni Forestry Station
Station codes	0302699W; 302669
Lat.(S); Long.(E)	28°39'; 30°53.1'
Altitude	1524m
Vegetation	*Aristida* grassland
Parent material	Natal group sandstone, Vryheid formation
Topography	South facing 7° slope
Years of data	43
Record span in years	51
Reliability index§	0.84

Profile exposed by digging back road cutting, 50m from rainguage.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	description
A	0 - 30	Moist; very dark brown (10YR 2/2); clay; apedal; porous; friable; humic phase; abundant roots; clear transition.
B1	30 - 100	Moist; yellowish brown (10YR 5/8); clay; apedal; porous; friable; apedal; few roots; gradual transition.
B2	100 - 120	Moist; brownish yellow (10YR 6/8); clay; apedal; porous; friable; apedal; rare roots; clear transition.
C	120+	Highly weathered sandstone.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1558.5	1108.4	390.6	394.3
Median (mm)	1523.6	1100.1	379.8	382.8
Sample Std. Dev. (mm)	264.00	139.00	119.20	123.57
Minimum (mm)	1096.5	819.2	156.0	152.8
Maximum (mm)	2218.3	1419.2	652.8	670.0
Lower quartile (mm)	1400.9	1044.8	310.1	308.6
Upper quartile (mm)	1723.7	1203.8	484.7	494.8
C.V.%	16.94	12.54	30.52	31.34
Standardized skewness	0.70	-0.21	0.27	0.32
Standardized kurtosis	-0.47	-0.22	-0.89	-0.89

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Qudeni										
Horizon[1]	A1	A2	AB	BA	B1	B2					B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-120
pH (KCl)	4.4	4.5	4.7	5.0	5.0	4.9	5.0	5.1	5.2	5.3	5.1
pH ($CaCl_2$)	4.5	4.6	4.7	4.8	4.9	4.8	4.9	4.9	5.1	5.1	4.9
pH (H_2O)	5.5	5.4	5.1	5.3	6.1	5.5	6.0	5.7	5.3	5.5	5.4
Texture											
Clay %	63	67	44	51	59	63	56	57	55	55	53
Silt %	24	19	25	14	20	17	20	18	17	17	15
Sand %		13	14	32	34	21	20	24	25	29	2 7 32
Exch. cations $cmol_c\ kg^{-1}$											
Ca	0.26	0.07	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
Mg	0.24	0.16	0.13	0.11	0.07	0.09	0.08	0.07	0.06	0.05	0.05
K	0.41	0.32	0.19	0.11	0.06	0.13	0.07	0.06	0.04	0.04	0.05
Na	0.17	0.14	0.10	0.07	0.10	0.07	0.06	0.06	0.07	0.08	0.06
acidity	2.61	1.83	0.95	0.22	0.25	0.26	0.17	0.15	0.17	0.12	0.11
ECEC	3.69	2.52	1.39	0.52	0.49	0.56	0.39	0.35	0.34	0.29	0.28
C %	19.15	14.87	10.14	4.91	4.81	3.43	2.24	1.95	1.65	1.48	1.47
N %	0.88	0.70	0.46	0.20	0.20	0.13	0.09	0.09	0.06	0.09	0.06
C/N	22	21	22	25	24	26	25	22	28	16	25
S-val/(clay)	1.71	1.02	1.00	0.59	0.41	0.48	0.39	0.35	0.31	0.31	0.32
Base sat %	29	27	32	58	49	54	56	57	50	59	61
LOI (430°C)	36.0	31.4	26.1	17.8	18.1	17.1	15.9	15.0	15.2	14.9	13.6

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Ntabamhlope Agricultural Research Station
Station codes	0268242A; ATS0270
Lat.(S); Long.(E)	29°02'; 29°39'
Altitude	1490m
Vegetation	*Themeda-Trachypogon* grassland
Parent material	Natal group sandstone
Topography	Flat
Years of data	31
Record span in years	31
Reliability index§	1.00

Pit dug adjacent to weather station.

Soil - Kp1100 clay
Form - Kranskop
Series - Fordoun

Horizon	depth (cm)	description
A	0 - 25	Moist; dark yellowish brown (10YR 4/6); clay; apedal; porous; friable; abundant roots; humic phase; frequent concretions; clear transition.
B1	25 - 45	Moist; yellowish brown (10YR 5/8); clay; apedal; porous; friable; abundant roots; frequent concretions; clear transition.
B2	45 - 120+	Moist; red (2.5YR 4/6); clay; apedal; porous; friable; abundant roots; frequent concretions; gradual increase in clay content with depth.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1097.8	902.1	220.3	225.7
Median (mm)	1018.3	850.4	183.8	188.8
Sample Std. Dev. (mm)	299.67	221.2	159.22	183.3
Minimum (mm)	716.8	605.0	33.2	31.5
Maximum (mm)	1858.0	1457.0	605.1	679.6
Lower quartile (mm)	881.6	757.5	104.0	85.8
Upper quartile (mm)	1198.0	956.2	264.6	274.2
C.V.%	27.3	24.52	72.26	81.19
Standardized skewness	2.71	2.49	2.63	2.73
Standardized kurtosis	0.88	0.64	0.65	0.76

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Ntabhamhlope

Horizon[1]	A		AB	B1	B2						
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100+
pH (KCl)	4.2	4.3	4.3	4.4	4.6	4.6	4.6	4.5	4.9	4.5	4.4
pH ($CaCl_2$)	4.2	4.4	4.5	4.6	4.8	4.8	4.6	4.7	4.9	4.6	4.4
pH (H_2O)	4.7	5.0	5.1	5.3	5.1	5.0	4.9	4.8	5.0	5.0	4.3
Texture											
Clay %	46	44	45	44	45	47	47	47	47	48	46
Silt %	11	9	11	11	10	9	11	9	9	8	7
Sand %	43	46	45	44	44	44	43	44	45	44	45
Exch. cations $cmol_c\ kg^{-1}$											
Ca	0.59	0.48	0.56	0.58	1.27	1.40	1.32	1.40	0.68	0.60	0.43
Mg	0.17	0.10	0.12	0.14	0.33	0.32	0.30	0.35	0.29	0.28	0.15
K	0.29	0.13	0.13	0.13	0.06	0.25	0.18	0.11	0.11	0.09	0.07
Na	0.14	0.10	0.11	0.08	0.12	0.07	0.08	0.07	0.08	0.07	0.06
acidity	2.16	2.04	1.37	0.59	0.20	0.23	0.34	0.21	0.07	0.35	0.78
ECEC	3.35	2.85	2.29	1.52	1.98	2.27	2.20	2.14	1.23	1.39	1.49
C %	3.39	3.25	2.32	1.56	1.02	0.83	0.73	0.48	0.30	0.35	0.32
N %	0.20	0.21	0.15	0.12	0.09	0.03	0.036	0.06	0.06	0.06	0.03
C/N	17	16	16	13	11	28	24	8	5	6	11
S-val/(clay)	2.59	1.84	2.04	2.11	3.96	4.34	3.96	4.11	2.47	2.17	1.54
Base sat %	36	28	40	61	90	90	85	90	94	75	48
LOI (430°C)	10.3	10.2	8.9	7.7	6.8	6.5	6.4	6.1	6.0	5.9	6.0

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Highmoor State Forestry Station
Station codes	0268199W
Lat.(S); Long.(E)	29°19.2'; 29°37.4'
Altitude	1981m
Vegetation	*Aristida* grassland
Parent material	Natal group sandstone
Topography	South-east facing 3° slope, upper midslope position
Years of data	31
Record span in years	35
Reliability index§	0.89

Samples taken from an excavated pit, 10m from rainguage.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	description
A	0 - 15	Moist; dark reddish brown (5YR 2.5/2); clay; apedal; porous; friable; frequent to abundant roots; few stones; rare concretions; excellent microstructure; clear transition.
B	15 - 45	Moist; yellowish red (5YR 4/6); clay; apedal; porous; friable; frequent roots; few stones; rare concretions; gradual transition.
C	45+	Sandstone parent material.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	1274.6	859.8	200.5	327.2
Median (mm)	1292.3	880.5	210.5	345.2
Sample Std. Dev. (mm)	273.10	135.67	73.32	126.94
Minimum (mm)	609.8	457.2	47.35	63.3
Maximum (mm)	1849.5	1097.2	317.5	523.4
Lower quartile (mm)	1022.6	755.1	139.5	225.9
Upper quartile (mm)	1486.7	956.3	252.4	410.6
C.V.%	21.43	15.78	36.56	38.79
Standardized skewness	-0.58	-1.56	-0.55	-0.58
Standardized kurtosis	-0.19	1.20	-0.87	-1.01

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Highmoor			
Horizon[1]	A	AB	B1	B2
Depth (cm)	0-10	10-20	20-30	30-40
pH (KCl)	4.4	4.5	4.9	5.0
pH ($CaCl_2$)	4.5	4.6	4.8	4.8
pH (H_2O)	5.4	5.5	5.6	5.5
Texture				
Clay %	63	56	62	57
Silt %	19	17	15	17
Sand %	18	28	23	26
Exch. cations $cmol_c\ kg^{-1}$				
Ca	1.77	0.40	0.32	0.33
Mg	0.90	0.40	0.25	0.26
K	0.82	0.50	0.26	0.25
Na	0.11	0.12	0.15	0.17
acidity	1.85	1.25	0.37	0.26
ECEC	5.45	2.67	1.35	1.27
C %	14.06	10.48	4.64	3.86
N %	0.75	0.59	0.32	0.24
C/N	19	18	15	16
S-val/(clay)	5.71	2.54	1.58	1.77
Base sat %	66	53	73	80
LOI (430°C)	29.2	24.7	20.3	16.1

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Camperdown
Station codes	0240073W
Lat.(S); Long.(E)	29°43'; 30°33'
Altitude	762m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Natal group sandstone, with possible doleritic influence
Topography	1° slope to the south-west
Years of data	61
Record span in years	76
Reliability index§	0.80

Samples taken from an excavated pit in open allotment, 50m from rainguage at the magistrate's offices.

Soil - Sd1220 clay
Form - Shortlands
Series - Sebati

Horizon	depth (cm)	description
A	0 - 35	Slightly moist; dark reddish brown (5YR 3/2); clay; moderate medium blocky; moderately porous; hard; few roots; common stones; clear transition.
B	35 - 120+	Moist; dark red (2.5YR 3/6); clay; strong fine subangular blocky; moderately porous; firm; rare roots; common stones.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	698.9	517.1	11.8	14.7
Median (mm)	672.5	508.0	0.0	0.0
Sample Std. Dev. (mm)	156.25	97.28	30.04	31.91
Minimum (mm)	432.0	337.0	0.0	0.0
Maximum (mm)	1167.0	750.0	157.3	163.6
Lower quartile (mm)	562.0	427.0	0.0	0.0
Upper quartile (mm)	782.5	569.0	6.9	12.9
C.V.%	22.36	18.81	254.4	217.79
Standardized skewness	2.48	1.65	12.81	11.99
Standardized kurtosis	0.20	-0.52	24.30	21.79

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Camperdown								
Horizon[1]	A1	A2		AB	BA	B1	B2		
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-65	65-80	80-90	90-110
pH (KCl)	4.8	4.8	4.8	4.6	4.9	5.2	5.4	5.5	5.6
pH ($CaCl_2$)	5.1	5.1	5.0	5.2	5.1	5.4	5.8	5.9	5.8
pH (H_2O)	6.0	5.8	5.9	6.0	5.9	6.0	6.1	6.0	6.3
Texture									
Clay %	47	48	49	51	65	77	81	83	82
Silt %	16	15	14	14	11	10	10	11	12
Sand %	37	37	36	36	24	13	8	6	6
Exch. cations $cmol_c\ kg^{-1}$									
Ca	4.45	4.65	4.21	4.06	3.76	3.80	4.26	4.27	4.76
Mg	2.47	2.55	2.51	2.49	2.78	3.02	3.33	3.45	3.84
K	0.44	0.37	0.23	0.25	0.17	0.15	0.15	0.13	0.12
Na	0.15	0.16	0.17	0.20	0.28	0.30	0.33	0.42	0.49
acidity	0.20	0.21	0.21	0.20	0.16	0.16	0.11	0.16	0.17
ECEC	7.71	7.94	7.33	7.20	7.15	7.43	8.18	8.43	9.38
C %	3.38	3.39	2.94	2.61	1.70	1.10	0.73	0.60	0.59
N %	0.24	0.22	0.14	0.16	0.15	0.09	0.09	0.09	0.06
C/N	14	15	21	16	11	12	8	7	10
S-val/(clay)	15.96	16.10	14.53	13.73	10.75	9.44	9.96	9.96	11.23
Base sat %	97	97	97	97	98	98	99	98	98
LOI (430°C)	9.1	8.4	7.9	7.6	6.8	6.8	6.7	6.0	6.2

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Freeland, Highflats (R.Fletcher)
Station codes	0210435A; ATS0251
Lat.(S); Long.(E)	30° 15'; 30° 15'
Altitude	914m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Natal group sandstone
Topography	5° slope to the north-west
Years of data	30
Record span in years	30
Reliability index§	1.00

Samples taken from a bank cut into the slope, 40m from farmhouse. Many sandstone boulders and rocks in the vicinity.

Soil - Ia1100 sandy clay loam
Form - Inanda
Series - Himeville

Horizon	depth (cm)	description
A	0 - 10	Moist; reddish brown (5YR 4/3); sandy clay loam; structureless; porous; friable; abundant roots; few stones; gradual transition.
B	10 - 35	Moist; dark reddish brown (5YR 3/4); sandy clay; apedal; porous; friable; frequent roots; clear transition.
C	35+	Sandstone saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	954.6	701.8	208.6	210.0
Median (mm)	916.1	687.0	197.3	201.7
Sample Std. Dev. (mm)	175.76	77.21	54.11	67.44
Minimum (mm)	708.7	569.5	101.4	79.4
Maximum (mm)	1560.7	864.8	329.1	365.7
Lower quartile (mm)	841.0	641.6	175.8	167.2
Upper quartile (mm)	1006.1	753.7	240.5	249.9
C.V.%	18.41	11.00	25.94	32.11
Standardized skewness	3.62	0.85	0.69	0.85
Standardized kurtosis	4.26	-0.46	-0.25	-0.12

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Freeland			
Horizon[1]	AB	BA	B1	B3
Depth (cm)	0-10	10-20	20-30	30-40
pH (KCl)	4.3	4.3	4.2	4.2
pH ($CaCl_2$)	4.6	4.4	4.4	4.3
pH (H_2O)	5.6	5.5	5.7	5.2
Texture				
Clay %	30	38	40	38
Silt %	8	8	9	12
Sand %	62	54	52	50
Exch. cations $cmol_c\ kg^{-1}$				
Ca	1.43	1.33	0.79	0.87
Mg	1.18	1.00	1.06	0.24
K	0.24	0.19	0.16	0.18
Na	0.20	0.16	0.15	0.20
acidity	0.46	0.82	0.94	0.98
ECEC	3.51	3.50	3.10	2.47
C %	3.28	3.00	3.35	2.02
N %	0.17	0.18	0.17	0.13
C/N	19	17	20	16
S-val/(clay)	10.17	7.05	5.40	3.92
Base sat %	87	77	70	60
LOI (430°C)	7.9	8.6	8.7	7.1

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Springbrook (abandoned farmhouse)
Station codes	0210285A; ATS0253
Lat.(S); Long.(E)	30° 15'; 30° 10'
Altitude	1066m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Ecca group shale
Topography	1° slope to the north-east
Years of data	48
Record span in years	50
Reliability index§	0.96

Samples taken from a pit excavated at the site of the old rainguage.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	description
A	0 - 30	Moist; dark brown (7.5YR 3/4); clay; moderate fine subangular blocky; porous; slightly hard; abundant roots; few stones; many concretions; especially at about 25cm; gradual transition.
B	30 - 55	Moist; brown (7.5YR 4/4); clay; apedal to weak fine subangular blocky; porous; friable; common roots; few stones; common concretions; a few shale chips in profile; clear transition.
C	55+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	746.4	541.5	31.5	26.6
Median (mm)	723.8	525.7	20.6	12.1
Sample Std. Dev. (mm)	144.83	83.57	41.19	39.33
Minimum (mm)	521.8	411.0	0.0	0.0
Maximum (mm)	1216.9	826.5	213.9	208.2
Lower quartile (mm)	647.8	481.8	3.2	0.0
Upper quartile (mm)	808.7	602.0	39.9	34.2
C.V.%	19.40	15.43	130.89	148.03
Standardized skewness	2.95	2.45	7.00	7.75
Standardized kurtosis	2.05	1.95	10.81	13.09

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Springbrook					
Horizon[1]	A1	A2	AB	BA	B1	B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60
pH (KCl)	4.0	3.9	4.0	4.3	4.2	4.3
pH ($CaCl_2$)	4.2	3.9	4.0	4.2	4.1	4.2
pH (H_2O)	5.2	5.2	5.3	5.3	5.3	5.3
Texture						
Clay %	57	60	59	73	74	73
Silt %	22	22	21	17	15	17
Sand %	21	18	20	11	11	10
Exch. cations $cmol_c\ kg^{-1}$						
Ca	2.15	1.87	1.50	1.40	1.96	1.25
Mg	1.66	1.30	1.02	0.98	0.94	1.26
K	0.18	0.15	0.16	0.15	0.21	0.10
Na	0.21	0.14	0.15	0.14	0.13	0.15
acidity	2.01	2.97	2.67	1.63	1.95	1.10
ECEC	6.21	6.43	5.50	4.30	5.19	3.86
C %	3.95	3.31	3.35	1.74	1.44	1.01
N %	0.25	0.20	0.17	0.13	0.08	0.10
C/N	16	17	20	13	18	10
S-val/(clay)	7.37	5.77	4.80	3.66	4.38	3.78
Base sat %	68	54	51	62	62	72
LOI (430°C)	12.6	11.8	10.8	11.0	11.7	10.8

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Stae Braes (T.G.English)
Station codes	0210301W
Lat.(S); Long.(E)	30°00.3'; 30°10.8'
Altitude	411m
Vegetation	*Acacia* thornveld
Parent material	Ecca group shale, Pietermaritzburg formation, with evidence of shale colluvium
Topography	5° slope to the south-west
Years of data	45
Record span in years	54
Reliability index§	0.83

Samples taken from an excavated pit adjacent to the approach road to the farmhouse.

Soil - Sd2120 clay
Form - Shortlands
Series - Roedtan

Horizon	depth (cm)	description
A	0 - 5	Slightly moist; reddish brown (5YR 4/3); clay; strong medium angular blocky; moderately porous; firm; common roots; common stones; gradual transition.
B	5 - 80	Moist; reddish brown (2.5YR 4/4); clay; strong medium angular blocky with distinct clay coatings on ped surfaces; moderately porous; firm; shale chips (evidence of colluvium); few roots; common stones; clear transition.
C	80+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	649.8	333.7	0.4	0.1
Median (mm)	626.6	323.7	0.0	0.0
Sample Std. Dev. (mm)	142.73	62.78	1.69	0.36
Minimum (mm)	368.2	210.8	0.0	0.0
Maximum (mm)	1095.0	486.2	10.0	2.7
Lower quartile (mm)	547.0	288.6	0.0	0.0
Upper quartile (mm)	735.4	367.5	0.0	0.0
C.V.%	21.96	18.82	480.52	728.01
Standardized skewness	2.28	1.48	15.19	21.64
Standardized kurtosis	1.03	-0.11	38.69	78.76

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Stae Braes				
Horizon[1]	AB	BA	B1	B2	B3
Depth (cm)	0-10	10-25	25-45	45-60	60-80
pH (KCl)	5.6	4.9	5.0	5.2	5.3
pH ($CaCl_2$)	5.9	5.8	5.6	5.8	5.9
pH (H_2O)	6.2	6.1	6.6	6.7	6.8
Texture					
Clay %	63	78	78	77	77
Silt %	16	13	13	13	13
Sand %	22	9	10	10	10
Exch. cations $cmol_c\ kg^{-1}$					
Ca	14.80	15.32	14.85	16.65	17.03
Mg	4.97	8.91	14.40	14.76	14.81
K	0.28	0.19	0.12	0.12	0.34
Na	0.64	0.50	0.43	0.47	0.49
acidity	0.06	0.09	0.09	0.07	0.05
ECEC	20.75	25.01	29.89	32.07	32.72
C %	2.48	0.70	0.62	0.50	0.50
N %	0.22	0.11	0.12	0.12	0.09
C/N	11	6	5	4	6
S-val/(clay)	32.84	31.95	38.21	41.56	42.43
Base sat %	100	100	100	100	100
LOI (430°C)	10.0	8.2	7.7	6.3	7.4

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Inglenook (Donnybrook)
Station codes	ATS0252; 0238682A
Lat.(S); Long.(E)	29°52'; 29°53'
Altitude	1280m
Vegetation	*Pennisetum clandestinum* grass
Parent material	Dolerite and Ecca group shale, Volksrust formation
Topography	1° slope to the south-west
Years of data	30
Record span in years	32
Reliability index§	0.94

Samples taken from a pit excavated in front of the farmhouse.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	description
A	0 - 30	Moist; dark reddish grey (5YR 4/2); clay; weak medium angular blocky; porous; slightly firm; frequent roots; few iron-manganese concretions; gradual transition.
B	30 - 90	Moist; red (2.5YR 4/6); clay; apedal; porous; friable; common roots; common iron-manganese concretions increasing with depth. A concretionary layer occurs at about 85cm.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	823.2	629.0	55.8	49.3
Median (mm)	805.5	636.1	40.5	35.6
Sample Std. Dev. (mm)	139.7	88.59	50.42	48.57
Minimum (mm)	528.7	433.0	0.5	0.0
Maximum (mm)	1206.4	819.2	221.3	213.7
Lower quartile (mm)	758.8	555.4	19.7	14.9
Upper quartile (mm)	879.9	708.4	78.2	71.2
C.V.%	16.97	14.08	90.28	98.46
Standardized skewness	1.71	-0.06	3.61	3.88
Standardized kurtosis	1.83	-0.45	3.35	3.93

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Inglenook

Horizon[1]	A		AB	BA		B1	B2
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-65	65-80
pH (KCl)	5.0	5.2	5.2	5.1	5.1	4.6	4.4
pH ($CaCl_2$)	5.5	5.7	5.7	5.6	5.7	5.2	4.6
pH (H_2O)	5.9	6.2	6.4	6.0	6.6	6.3	5.9
Texture							
Clay %	53	57	65	66	67	67	64
Silt %	20	19	16	15	15	16	14
Sand %	26	24	20	19	18	17	22
Exch. cations $cmol_c\ kg^{-1}$							
Ca	10.43	6.38	6.59	3.58	3.41	1.72	1.83
Mg	3.86	3.55	3.48	3.19	3.84	2.18	2.22
K	0.99	0.77	0.80	0.64	0.73	0.66	0.50
Na	0.24	0.18	0.19	0.16	0.17	0.14	0.09
acidity	0.08	0.07	0.07	0.09	0.09	0.15	0.40
ECEC	15.60	10.95	11.13	7.66	8.24	4.85	5.04
C %	5.71	3.27	2.40	2.28	1.91	1.36	0.93
N %	0.22	0.20	0.08	0.11	0.06	0.06	0.03
C/N	26	16	30	21	32	23	31
S-val/(clay)	29.28	19.09	17.02	11.47	12.16	7.01	7.25
Base sat %	99	99	99	99	99	97	92
LOI (430°C)	15.2	11.1	10.6	10.6	9.7	7.6	7.5

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Lilydale (Donnybrook)
Station codes	ATS0305; 0238840A
Lat.(S); Long.(E)	30°00'; 29°58'
Altitude	1330m
Vegetation	Sparse *Themeda-Hyparrhenia* grassland
Parent material	Ecca group shale, Volksrust formation, with dolerite in vicinity
Topography	5° slope to the south-west
Years of data	38
Record span in years	40
Reliability index§	0.95

Samples taken from an excavated pit adjacent to the approach road to the farmhouse.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

<u>Horizon</u>	<u>depth (cm)</u>	<u>description</u>
A	0 - 15	Moist; brown (7.5YR 4/2); clay; friable; porous; apedal; common roots; few stones; gradual transition.
B	15 - 70	Moist; brown (7.5YR 4/4); clay; apedal; porous; friable; gradual transition.
C	70+	Shale saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	769.5	544.0	35.1	31.3
Median (mm)	753.1	537.6	23.5	19.9
Sample Std. Dev. (mm)	115.15	63.47	30.33	29.05
Minimum (mm)	454.6	356.8	0.0	0.0
Maximum (mm)	1017.1	658.9	131.0	123.4
Lower quartile (mm)	707.0	509.1	14.8	11.3
Upper quartile (mm)	846.6	591.3	49.1	42.0
C.V.%	14.96	11.67	86.47	92.85
Standardized skewness	-0.19	-1.10	2.97	3.13
Standardized kurtosis	0.41	1.11	1.67	1.78

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Lilydale

Horizon[1]	A	AB	BA	B1	B2	B3
Depth (cm)	0-10	10-20	20-35	35-50	50-60	60-70
pH (KCl)	4.5	4.0	4.0	4.0	4.0	4.0
pH ($CaCl_2$)	4.7	4.0	4.2	4.3	4.2	4.2
pH (H_2O)	5.2	4.7	4.8	5.0	4.8	4.8
Texture						
Clay %	67	69	72	72	74	75
Silt %	20	18	15	12	15	13
Sand %	14	13	13	16	11	12
Exch. cations $cmol_c\ kg^{-1}$						
Ca	3.91	2.88	1.44	0.95	0.87	0.66
Mg	2.81	1.80	1.48	1.45	1.31	1.00
K	0.80	0.82	0.69	0.67	0.56	0.33
Na	0.31	0.22	0.18	0.20	0.20	0.15
acidity	0.26	0.38	0.79	0.79	0.89	0.97
ECEC	8.09	6.10	4.58	4.06	3.83	3.11
C %	5.94	4.65	4.29	3.43	3.06	2.48
N %	0.43	0.28	0.21	0.18	0.17	0.13
C/N	14	17	20	19	18	19
S-val/(clay)	11.69	8.29	5.26	4.54	3.97	2.85
Base sat %	97	94	83	81	77	69
LOI (430°C)	16.7	15.2	14.8	14.0	13.2	9.7

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Bray Hill farm
Station codes	ATS0323; 0268670A
Lat.(S); Long.(E)	29°10'; 29°53'
Altitude	1524m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Natal group sandstone
Topography	2° slope to the west
Years of data	36
Record span in years	38
Reliability index§	0.95

Samples taken from an excavated pit.

Soil - Ma1100 clay
Form - Magwa
Series - Glenesk

Horizon	depth (cm)	description
A	0 - 10	Moist; dark brown (10YR 3/3); clay; friable; porous; apedal; common roots; gradual transition.
B	10 - 40	Moist; yellowish brown (10YR 5/4); clay; apedal; porous; friable; gradual transition.
C	40+	Sandstone saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	858.0	658.1	181.5	198.1
Median (mm)	842.0	654.8	182.2	195.5
Sample Std. Dev. (mm)	168.41	103.24	71.89	90.22
Minimum (mm)	603.5	493.0	65.3	55.2
Maximum (mm)	1284.3	932.3	399.4	462.4
Lower quartile (mm)	713.2	564.4	130.4	137.6
Upper quartile (mm)	972.8	725.6	233.4	268.7
C.V.%	19.63	15.69	39.61	45.54
Standardized skewness	1.40	1.16	1.50	1.38
Standardized kurtosis	-0.15	-0.20	0.92	0.53

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile :	Bray Hill			
Horizon[1]	AB	BA	B1	B3
Depth (cm)	0-10	10-20	20-30	30-40
pH (KCl)	3.7	3.8	3.9	3.9
pH ($CaCl_2$)	3.7	3.9	4.1	4.0
pH (H_2O)	4.5	4.7	5.0	5.1
Texture				
Clay %	46	46	46	46
Silt %	12	12	12	12
Sand %	42	42	41	42
Exch. cations $cmol_c\ kg^{-1}$				
Ca	1.05	1.22	1.20	0.83
Mg	0.62	0.55	0.50	0.40
K	0.76	0.65	0.63	0.44
Na	0.28	0.13	0.11	0.11
acidity	3.38	2.83	2.64	2.72
ECEC	6.09	5.38	5.08	4.50
C %	6.79	4.83	3.50	3.76
N %	0.45	0.31	0.25	0.23
C/N	15	16	14	16
S-val/(clay)	5.89	5.54	5.30	3.87
Base sat %	44	47	48	40
LOI (430°C)	15.0	11.0	9.5	9.8

[1]1991 Nomenclature (Soil Classification Working Group (1991))

Locality	Kilmoshogue farm (P.Elliott)
Station codes	ATS0250; 0268640A
Lat.(S); Long.(E)	29°10'; 29°52'
Altitude	1520m
Vegetation	*Themeda-Hyparrhenia* grassland
Parent material	Natal group sandstone
Topography	1° slope to the north-east
Years of data	79
Record span in years	81
Reliability index§	0.98

Samples taken from excavated pit, 50m from farmhouse.

Soil - Ia1100 clay
Form - Inanda
Series - Himeville

Horizon	depth (cm)	description
A	0 - 10	Moist; dark brown (7.5YR 3/4); clay; friable; porous; apedal; common roots; gradual transition.
B	10 - 70	Moist; reddish brown (5YR 4/4); clay; apedal; porous; friable; gradual transition.
C	70+	Sandstone saprolite.

Climatic information

	Annual rainfall	Effective rainfall*	Drainage out of the B1 horizon*	Drainage at a soil depth of 50cm*
Mean (mm)	874.9	673.5	186.5	193.3
Median (mm)	879.7	670.4	191.5	191.6
Sample Std. Dev. (mm)	165.25	110.39	78.54	95.12
Minimum (mm)	553.4	458.2	32.0	27.7
Maximum (mm)	1436.6	1004.5	396.9	463.8
Lower quartile (mm)	757.4	599.9	127.0	117.8
Upper quartile (mm)	967.2	743.1	242.0	249.4
C.V.%	18.89	16.39	42.12	49.22
Standardized skewness	1.87	1.30	1.59	2.30
Standardized kurtosis	1.44	0.56	0.22	0.76

§ratio of years of data:record span in years
*as modelled by ACRU

Analytical data

Profile : Kilmoshogue

Horizon[1]	AB	BA	B1	B2			B3
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70
pH (KCl)	3.8	3.9	4.0	4.1	4.0	4.1	3.8
pH ($CaCl_2$)	4.1	4.1	4.0	4.7	4.1	4.1	4.1
pH (H_2O)	4.7	4.8	4.7	4.9	4.9	4.9	4.5
Texture							
Clay %	43	45	45	44	45	45	46
Silt %	14	13	14	12	13	11	12
Sand %	42	42	42	43	42	44	43
Exch. cations $cmol_c\ kg^{-1}$							
Ca	3.06	2.11	1.07	0.74	0.74	0.79	0.82
Mg	0.96	0.88	0.50	0.42	0.42	0.49	0.52
K	0.52	0.58	0.58	0.31	0.31	0.24	0.18
Na	0.12	0.12	0.10	0.12	0.12	0.11	0.11
acidity	1.30	1.88	2.38	2.14	2.02	1.97	2.08
ECEC	5.96	5.57	4.63	3.73	3.61	3.60	3.71
C %	5.15	3.47	2.90	2.25	1.80	1.40	1.12
N %	0.28	0.20	0.15	0.10	0.10	0.07	0.06
C/N	18	17	19	23	18	20	19
S-val/(clay)	10.84	8.20	5.00	3.61	3.53	3.62	3.54
Base sat %	78	66	49	43	44	45	44
LOI (430°C)	11.4	9.1	8.0	7.1	6.4	5.1	5.4

[1] 1991 Nomenclature (Soil Classification Working Group (1991))

APPENDIX B

Laboratory methods of analysis

LABORATORY METHODS OF ANALYSIS

All samples were sieved through a 2mm screen and air-dried for at least 48 hours before being bottled. A gravel% was determined as that percentage of the original soil sample that did not pass through a 2mm screen after the soil peds had been broken up.

All subsequent determinations were made on the screened soil and where appropriate, a moisture factor was determined in order to express all results in terms of an oven-dry mass. The moisture factor was determined by weighing an air-dried soil sample before and after being oven-dried at 105°C, and the moisture factor was calculated as the ratio of the mass of the air-dried soil to the oven-dried soil.

B.1 Physical Methods

B.1.1 Soil Textural Analysis

The pipette method was used to determine soil texture. Air-dried soil samples (10g) were pretreated with 30% H_2O_2 (10ml) to remove organic matter by oxidation. Dispersion of the soil samples was achieved by the addition of Calgon (a sodium hexametaphosphate and sodium carbonate solution) and the soil slurries were then subjected to ultrasound (20kHz) at 350 Watts for approximately 3 minutes using a probe sonicator (Braun Ultrasonic-Homogenizer Labsonic U).

Clay (< 2μm settling diameter) and silt (2-20μm) fractions were determined by sedimentation and pipette sampling and expressed as a percentage of oven-dried soil (Day, 1965). The sand fraction (0.02 - 2mm) was determined by difference from 100%.

B.1.2 Specific Surface Area

Specific surface area (SSA) was measured by ethylene glycol monoethyl ether (EGME) retention following a method similar to that of Smith *et al.* (1985) and Carter *et al.* (1986). Soil samples in tared pill vials were oven dried at 105°C for 24 hours and weighed. A small amount of ethylene glycol monoethyl ether was added to each soil and allowed to equilibrate under vacuum and anhydrous conditions (using $CaCl_2$), and weighed when constant mass had been achieved. SSA was calculated from the equation:

$$SSA\ (m^2g^{-1}) = M_a/(M_s \times 0.000286)$$

where M_a = mass of EGME retained by the sample in g, and M_s = mass of oven-dried soil in g, and 0.000286g is the mass of EGME required to form a monomolecular layer on a square meter of surface (Carter *et al.*, 1986).

B.2 General Chemical Methods

B.2.1 Soil pH determinations

Three soil pHs' were determined for each soil sample. The equilibrating solutions used were deionized water, 0.01M $CaCl_2$ and 1M KCl. In each case 10g of soil was shaken up in a stoppered vial with 25ml of the equilibrating solution (giving a soil:solution ratio of 1:2.5), and the pH of the resulting supernatant was read using a standard glass electrode (Metrohm Hersiau E396B) after the vial had been left to stand overnight.

B.2.2 Loss-on-Ignition

Thermogravimetric loss-on-ignition was determined by the ignition of the soil sample at 430°C for at least 4 hours and is expressed as a percentage of oven-dry mass (Donkin, 1991).

B.2.3 Organic Matter determination

The oxidizable organic carbon fraction in the soil was determined using the wet oxidation technique according to Walkley (1947), commonly referred to as the Walkley-Black method. Air-dry soil is ground to pass a 0.5mm screen. Soil is then digested in a potassium dichromate/sulphuric acid mix in which the organic matter is oxidized. Soil organic matter content is determined by back-titration of the excess dichromate, using a 0.5N ferrous ammonium sulphate solution.

B.2.4 Organic Nitrogen determination

Soil organic nitrogen is determined through the sulphuric acid digestion of organic nitrogen to ammonium sulphate, with a subsequent determination of ammonium ions, using selenium as a catalyst (FRI Bulletin no.70, p.13). Under alkaline conditions, ammonia is distilled into a boric acid solution and then back-titrated with a standardized solution of HCl. The soil organic nitrogen content is expressed in percentage terms of the oven-dried soil sample.

B.2.5 C/N ratio

The C/N ratio is determined as the ratio of Walkley-Black organic carbon to soil organic nitrogen as determined by the Kjeldahl method.

B.2.6 Exchangeable cations

Soil samples were equilibrated with 1M ammonium acetate (pH 7) for 10 minutes in stoppered centrifuge bottles on a tumbler. The resulting slurry was then centrifuged to 3000rpm and then filtered through Whatman 41 filter paper. The filtrate was suitably diluted and appropriate ionization suppressants were added. The basic cations in the solution (calcium, magnesium, potassium and sodium) were determined using atomic absorption and flame emission spectroscopy (Varian AA 10B instrument), and expressed in $cmol_c\ kg^{-1}$ soil.

The sum of the exchangeable basic cations is known as the so-called S-value:

$$\text{S-value} = \Sigma \text{ exchangeable } (Ca^{2+} + Mg^{2+} + K^{+} + Na^{+})$$

B.2.7 Exchangeable Acidity

Soil samples were equilibrated with unbuffered 1N potassium chloride, centrifuged at 3000rpm and then filtered through Whatman 41 filter paper. An aliquot of filtrate was titrated against a standardized NaOH solution using an autotitrator. The potentiometric endpoint was set at a pH of 8.40. Exchangeable acidity is expressed in terms of $cmol_c kg^{-1}$ soil.

B.2.8 Cation Exchange Capacity

The Effective Cation Exchange Capacity (ECEC) was calculated as the sum of the exchangeable cations and the exchangeable acidity measured above, a procedure recommended for highly weathered soils in the tropics (Juo *et al.*, 1976; Juo, 1981).

$$\text{ECEC} = \Sigma \text{ exchangeable}(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+} + \text{acidity})\ cmol_c\ kg^{-1} \text{ soil}$$

The modified ECEC referred to in section 3.2.2.1 and in the discussion section 5.2, is the ECEC defined above, but with the exclusion of the monovalent cations K^+ and Na^+:

$$\text{Modified ECEC} = \Sigma \text{ exchangeable}(Ca^{2+} + Mg^{2+} + \text{acidity}) \text{ cmol}_c \text{ kg}^{-1} \text{ soil}$$

B.2.9 Base Saturation Percentage

Base Saturation Percentage was calculated as the proportion of the effective cation exchange capacity occupied by the basic cations, expressed as a percentage.

$$\text{Base saturation \%} = \frac{\text{S-value} * 100}{\text{ECEC}} \%$$

B.2.10 Bray-2 Exchangeable Phosphorus

A mixed extractant of 0.03M NH_4F in 0.1M HCl (known as Bray-2 extractant) has been found to be an effective extractant of available phosphorus, particularly for acid soils. The methodology used followed that of Bray and Kurtz (1945). Soil samples were equilibrated with Bray-2 extractant for 5 minutes in stoppered centrifuge bottles on a tumbler. The resulting slurry was then centrifuged to 3000rpm and then filtered through Whatman 41 filter paper. Available phosphorus was determined colorimetrically at 880nm on an automated segmented flow analyzer (SKALAR SAN^{plus}SYSTEM) using the molybdenum blue complex method.

B.3 Mineralogical methods

B.3.1 X-ray fluorescence analysis (XRF)

XRF analyses were performed by Roy Seyambu of the Department of Geology and Mineralogy (Pietermaritzburg). Air-dried soil samples were fused with flux in platinum crucibles at 1000°C and formed into glass disks. The disks were then analyzed spectroscopically using a Philips PW1410 XRF instrument and the total major elemental concentrations of Si, Al, Fe, Mn, Mg, Ca, Na, K, Ti, P, Cr and Ni expressed in terms of their oxide percent.

B.4 Soil Solution Analyses

Two soil solutions were obtained:

1. 10g soil was equilibrated with 20ml deionized water in polypropylene containers for 7 days on a reciprocating shaker operating at 120 oscillations per minute. The solutions were centrifuged and then filtrated through Whatman 42 filter paper. Those soils that possessed dispersive clays, giving rise to excessive turbidity in the filtrate, were subsequently filtered using syringe filters, fitted with Sartorius cellulose nitrate membrane filters (SM 11306) of pore size 0.45μm and diameter 25mm, and Sartorius glass fibre prefilters (SM 13400) of diameter 20mm, before analysis. All analytical results were expressed on an oven-dry mass basis.

2. 10g soil was equilibrated with 50ml 0.01M $CaCl_2$ in polypropylene containers for 8 hours with intermittent shaking, and were then allowed to settle. The soil solution was decanted and filtered through Whatman 42 filter paper. None of the soils proved to be sufficiently dispersive in this equilibrating solution to warrant centrifugation or membrane filtration.

Solution Si was determined according to the silicomolybdous blue procedure (Hallmark *et al.*, 1982) on both sets of solutions, and expressed in terms of the negative logarithm of the silicic acid activity, i.e. pH_4SiO_4. Electrical conductivity (EC), followed by pH were also determined on the 1:2 soil:water solution set according to the methodology of Rhoades (1986). EC was determined using a Radiometer CDM83 conductivity meter with temperature compensation, and pH was determined using a Metrohm Herisau E396B pH meter.

APPENDIX C

Soil property - climate relationships related to soil samples from the (i) A-horizon; (ii) from a depth of 50cm; and (iii) the B1 horizon (not reported in the main body of the thesis).

C.1 Relationships between soil properties of A-horizon soil samples and the indices of climate MAP and MAER.

All soils (n=33):

1	MAP	1.00						
2	MAER	0.94***	1.00					
3	Clay %	0.01	-.17	1.00				
4	ln(S-value)	-.32	-.22	-.65***	1.00			
5	ln(S-val/unit clay)	-.38*	-.32	-.46**	0.97***	1.00		
6	ln(Ca+Mg)	-.45**	-.43*	-.17	0.85***	0.95***	1.00	
7	ln((Ca+Mg)/unit clay)	-.41*	-.35*	-.43*	0.96***	0.99***	0.96***	1.00
		1	2	3	4	5	6	7

1	MAP	1.00						
2	MAER	0.94***	1.00					
3	Base saturation %	-.41*	-.37*	1.00				
4	Dibasic cation %[1]	-.41*	-.35*	0.88***	1.00			
5	ln(exch.Ca)	-.43	-.40*	0.93***	0.85***	1.00		
6	ln(exch.Mg)	-.44*	-.46**	0.86***	0.69***	0.85***	1.00	
7	Ca/Mg	0.01	0.16	0.12	0.27	0.28	-.22	1.00
		1	2	3	4	5	6	7

1	MAP	1.00					
2	MAER	0.94***	1.00				
3	lnECEC	-.36*	-.39*	1.00			
4	lnECEC/unit clay	-.32	-.27	0.90***	1.00		
5	ln(Ca+Mg+acidity)	-.36*	-.40*	1.00***	0.89***	1.00	
6	ln((Ca+Mg+acidity)/clay)	-.32	-.28	0.91***	1.00***	0.91***	1.00
		1	2	3	4	5	6

1	MAP	1.00								
2	MAER	0.94***	1.00							
3	pH (KCl)	-.27	-.32	1.00						
4	pH ($CaCl_2$)	-.29	-.30	0.94***	1.00					
5	pH (H_2O)	-.21	-.25	0.86***	0.91***	1.00				
6	ln(exch. acidity)	0.40*	0.39*	-.66***	-.67***	-.60***	1.00			
7	Org.C%	0.75***	0.59***	-.20	-.30	-.12	0.36*	1.00		
8	Org.N%	0.68***	0.52**	-.19	-.29	-.12	0.37*	0.95***	1.00	
9	LOI	0.74***	0.60***	-.27	-.36*	-.19	0.37*	0.95***	0.91***	1.00
		1	2	3	4	5	6	7	8	9

[1](Exch. Ca + Mg) x 100/(Exch. Ca + Mg + acidity)

C.2 Relationships between soil properties of samples taken from a depth of 50cm in the soil profile, and the climatic indices MAP, MAER and mean annual drainage from the 50cm depth in the profile (MAD [50cm]).

All soils (n=33):

1	MAP	1.00							
2	MAER	0.94***	1.00						
3	MAD [50cm]	0.86***	0.82***	1.00					
4	Clay %	-.20	-.30	-.27	1.00				
5	ln(S-value)	-.73***	-.76***	-.63***	0.06	1.00			
6	ln(S-value/unit clay)	-.69***	-.69***	-.58***	-.14	0.98***	1.00		
7	ln(Ca+Mg)	-.77***	-.78***	-.66***	0.09	0.99***	0.96***	1.00	
8	ln((Ca+Mg)/unit clay)	-.73***	-.72***	-.62***	-.08	0.97***	0.99***	0.98***	1.00
		1	2	3	4	5	6	7	8

Soils derived from shale (n=13):

1	MAP	1.00							
2	MAER	0.98***	1.00						
3	MAD [50cm]	0.91***	0.87***	1.00					
4	Clay %	-.57*	-.66*	-.51	1.00				
5	ln(S-value)	-.67*	-.72**	-.49	0.42	1.00			
6	ln(S-value/unit clay)	-.63*	-.67*	-.45	0.31	0.99***	1.00		
7	ln(Ca+Mg)	-.73**	-.78***	-.56*	0.50	0.98***	0.97***	1.00	
8	ln((Ca+Mg)/unit clay)	-.71**	-.74**	-.53	0.41	0.99***	0.98***	1.00***	1.00
		1	2	3	4	5	6	7	8

Soils derived from dolerite (n=11):

1	MAP	1.00							
2	MAER	0.95***	1.00						
3	MAD [50cm]	0.89***	0.79**	1.00					
4	Clay %	0.14	0.09	0.06	1.00				
5	ln(S-value)	-.75**	-.82**	-.62*	-.28	1.00			
6	ln(S-value/unit clay)	-.72*	-.78**	-.59*	-.48	0.98***	1.00		
7	ln(Ca+Mg)	-.72*	-.80***	-.59	-.28	1.00***	0.97***	1.00	
8	ln((Ca+Mg)/unit clay)	-.70*	-.76**	-.56	-.47	0.98***	1.00***	0.98***	1.00
		1	2	3	4	5	6	7	8

Soils derived from sandstone (n=9):

1	MAP	1.00							
2	MAER	0.95***	1.00						
3	MAD [50cm]	0.84**	0.75*	1.00					
4	Clay %	0.13	-.06	-.02	1.00				
5	ln(S-value)	-.78*	-.66	-.81**	-.31	1.00			
6	ln(S-value/unit clay)	-.74*	-.59	-.74*	-.49	0.98***	1.00		
7	ln(Ca+Mg)	-.80**	-.67*	-.82**	-.33	0.99***	0.98***	1.00	
8	ln((Ca+Mg)/unit clay)	-.77*	-.62	-.77*	-.47	0.98***	1.00***	0.99***	1.00
		1	2	3	4	5	6	7	8

All soils (n=33):

1	MAP	1.00				
2	MAER	0.94***	1.00			
3	MAD [50cm]	0.86***	0.82***	1.00		
4	base saturation %	-.37*	-.39**	-.33	1.00	
5	dibasic cation sat%[2]	-.51**	-.51**	-.51**	0.88***	1.00
		1	2	3	4	5

Shale (n=13):

1	MAP	1.00				
2	MAER	0.98***	1.00			
3	MAD [50cm]	0.91***	0.87***	1.00		
4	base saturation %	-.49	-.53	-.32	1.00	
5	dibasic cation sat%	-.68*	-.69**	-.60*	0.64*	1.00
		1	2	3	4	5

Dolerite (n=11):

1	MAP	1.00				
2	MAER	0.95***	1.00			
3	MAD [50cm]	0.89***	0.79**	1.00		
4	base saturation %	-.55	-.58	-.50	1.00	
5	dibasic cation sat%	-.54	-.56	-.48	1.00***	1.00
		1	2	3	4	5

Sandstone (n=9):

1	MAP	1.00				
2	MAER	0.95***	1.00			
3	MAD [50cm]	0.84**	0.75*	1.00		
4	base saturation %	-.10	-.00	-.26	1.00	
5	dibasic cation sat%	-.27	-.16	-.41	0.98***	1.00
		1	2	3	4	5

All soils (n=33):

1	MAP	1.00					
2	MAER	0.94***	1.00				
3	MAD [50cm]	0.86***	0.82***	1.00			
4	ln(exch.Ca)	-.71***	-.68***	-.57***	1.00		
5	ln(exch.Mg)	-.76***	-.81***	-.70***	0.81***	1.00	
6	Ca/Mg	0.14	0.24	0.20	0.18	-.38*	1.00
		1	2	3	4	5	6

[2](Exch. Ca + Mg) x 100/(Exch. Ca + Mg + acidity)

Shale derived soils (n=13):

1	MAP	1.00						
2	MAER	0.98***	1.00					
3	MAD 50cm]	0.91***	0.87***	1.00				
4	ln(exch.Ca)	-.61*	-.64*	-.41	1.00			
5	ln(exch.Mg)	-.83***	-.87***	-.68**	0.87***	1.00		
6	Ca/Mg	0.56*	0.56*	0.62*	0.14	-.34	1.00	
		1	2	3	4	5	6	

Dolerite derived soils (n=11):

1	MAP	1.00					
2	MAER	0.95***	1.00				
3	MAD [50cm]	0.89***	0.79**	1.00			
4	ln(exch.Ca)	-.48	-.56	-.39	1.00		
5	ln(exch.Mg)	-.84**	-.90***	-.69*	0.68*	1.00	
6	Ca/Mg	0.44	0.46	0.33	0.17	-.53	1.00
		1	2	3	4	5	6

Sandstone derived soils (n=9):

1	MAP	1.00					
2	MAER	0.95***	1.00				
3	MAD [50cm]	0.84**	0.75*	1.00			
4	ln(exch.Ca)	-.85**	-.73*	-.81**	1.00		
5	ln(exch.Mg)	-.64	-.53	-.66	0.80**	1.00	
6	Ca/Mg	-.34	-.28	-.39	0.31	-.28	1.00
		1	2	3	4	5	6

All soils (n=33):

1	MAP	1.00						
2	MAER	0.94***	1.00					
3	MAD [50cm]	0.86***	0.82***	1.00				
4	pH (1M KCl)	-.12	-.26	-.14	1.00			
5	pH (0.01M $CaCl_2$)	-.23	-.33	-.23	0.94***	1.00		
6	pH (H_2O)	-.20	-.33	-.20	0.83***	0.88***	1.00	
7	ln(exch. acidity)	0.12	0.20	0.16	-.75***	-.77***	-.68**	1.00
		1	2	3	4	5	6	

Shale derived soils (n=13):

1	MAP	1.00						
2	MAER	0.98***	1.00					
3	MAD [50cm]	0.91***	0.87***	1.00				
4	pH (1M KCl)	-.39	-.43	-.34	1.00			
5	pH (0.01M $CaCl_2$)	-.40	-.48	-.29	0.91***	1.00		
6	pH (H_2O)	-.60*	-.65*	-.40	0.74**	0.83***	1.00	
7	ln(exch. acidity)	0.29	0.33	0.21	-.58*	-.56*	-.39	1.00
		1	2	3	4	5	6	

Dolerite derived soils (n=11):

1	MAP	1.00						
2	MAER	0.95^{***}	1.00					
3	MAD [50cm]	0.89^{***}	0.79^{**}	1.00				
4	pH (1M KCl)	-.37	-.53	-.18	1.00			
5	pH (0.01M $CaCl_2$)	-.37	-.50	-.21	0.98^{***}	1.00		
6	pH (H_2O)	-.32	-.40	-.27	0.88^{***}	0.93^{***}	1.00	
7	ln(exch. acidity)	0.43	0.52	0.36	$-.81^{**}$	$-.88^{***}$	$-.89^{***}$	1.00
		1	2	3	4	5	6	

Sandstone derived soils (n=9):

1	MAP	1.00						
2	MAER	0.95^{***}	1.00					
3	MAD [50cm]	0.84^{**}	0.75^{*}	1.00				
4	pH (1M KCl)	0.51	0.48	0.19	1.00			
5	pH (0.01M $CaCl_2$)	0.25	0.34	-.10	0.92^{***}	1.00		
6	pH (H_2O)	0.40	0.37	0.15	0.85^{**}	0.82^{**}	1.00	
7	ln(exch. acidity)	-.37	-.39	-.11	$-.94^{***}$	$-.90^{***}$	$-.75^{*}$	1.00
		1	2	3	4	5	6	

All soils (n=33):

1	MAP	1.00						
2	MAER	0.94^{***}	1.00					
3	MAD [50cm]	0.86^{***}	0.82^{***}	1.00				
4	ln(ECEC)	$-.78^{***}$	$-.80^{***}$	$-.67^{***}$	1.00			
5	ln(ECEC/unit clay)	$-.73^{***}$	$-.72^{***}$	$-.60^{***}$	0.97^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.77^{***}$	$-.78^{***}$	$-.64^{***}$	0.98^{***}	0.95^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.72^{***}$	$-.71^{***}$	$-.58^{***}$	0.96^{***}	0.98^{***}	0.97^{***}	1.00
		1	2	3	4	5	6	7

Shale derived soils (n=13):

1	MAP	1.00						
2	MAER	0.98^{***}	1.00					
3	MAD [50cm]	0.91^{***}	0.87^{***}	1.00				
4	ln(ECEC)	$-.70^{**}$	$-.76^{**}$	-.52	1.00			
5	ln(ECEC/unit clay)	$-.65^{*}$	$-.70^{**}$	-.48	0.99^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.68^{*}$	$-.73^{**}$	$-.49^{*}$	0.96^{***}	0.94^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.64^{*}$	$-.69^{**}$	-.45	0.96^{***}	0.96^{***}	0.99^{***}	1.00
		1	2	3	4	5	6	7

Dolerite derived soils (n=11):

1	MAP	1.00						
2	MAER	0.95^{***}	1.00					
3	MAD [50cm]	0.89^{***}	0.79^{**}	1.00				
4	ln(ECEC)	$-.70^{*}$	$-.79^{**}$	-.57	1.00			
5	ln(ECEC/unit clay)	$-.67^{*}$	$-.72^{*}$	-.53	0.97^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.67^{*}$	$-.76^{**}$	-.54	1.00^{***}	0.97^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.64^{*}$	$-.70^{*}$	-.50	0.97^{***}	1.00^{***}	0.97^{***}	1.00
		1	2	3	4	5	6	7

Sandstone derived soils (n=9):

1	MAP	1.00						
2	MAER	0.95^{***}	1.00					
3	MAD [50cm]	0.84^{**}	0.75^{*}	1.00				
4	ln(ECEC)	$-.92^{***}$	$-.81^{**}$	$-.90^{**}$	1.00			
5	ln(ECEC/unit clay)	$-.87^{**}$	$-.72^{*}$	$-.81^{**}$	0.97^{***}	1.00		
6	ln(Ca + Mg + acidity)	$-.93^{***}$	$-.81^{**}$	$-.91^{***}$	1.00^{***}	0.97^{***}	1.00	
7	ln((Ca + Mg + acidity)/clay)	$-.88^{**}$	$-.73^{*}$	$-.83^{**}$	0.98^{***}	1.00^{***}	0.98^{***}	1.00
		1	2	3	4	5	6	7

C.3 Relationships between soil properties of samples taken from the B1 horizon and the climatic indices MAP, MAER and mean annual drainage from the B1 horizon (MAD [B1]), *not* reported in the main body of the thesis.

All soils (n=33)

1	MAP	1.00					
2	MAER	0.94^{***}	1.00				
3	MAD [B1]	0.84^{***}	0.81^{***}	1.00			
4	Org.C%	0.49^{**}	0.36^{**}	0.47^{**}	1.00		
5	Org.N%	0.29	0.13	0.38^{*}	0.81^{***}	1.00	
6	LOI	0.61^{***}	0.46^{**}	0.43^{*}	0.72^{***}	0.53^{**}	1.00
		1	2	3	4	5	6

APPENDIX D

X-Ray Fluorescence analytical data

Total elemental analysis

33 B1 soil samples (< 2mm) were analysed by XRF using a PW1404 x-ray spectrometer. Samples were first ignited at 1000°C and fused into discs. Elemental composition on each sample was expressed in terms of oxide percent of the non-volatile soil fraction. SiO_2/Al_2O_3 and SiO_2/R_2O_3 ratios were calculated on the basis of their molecular equivalents. R_2O_3 refers to the sesquioxides Fe_2O_3 + Al_2O_3.

Total Elemental Analysis of untreated <2mm fraction B21 soil samples on a non-volatile (1000°C) basis:

Sample	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SiO_2/Al_2O_3	SiO_2/R_2O_3	Total (%)
Bloemendal	41.80	33.63	21.74	2.10	1.50	99.95
Cedara	50.44	23.52	23.28	3.63	2.24	100.14
Windy Hill	75.61	15.67	6.67	8.20	6.45	99.85
Eston	48.49	30.85	17.94	2.66	1.95	99.94
Harmony	56.14	23.47	17.60	5.41	2.75	100.29
Dargle	65.81	22.23	9.31	5.02	3.97	99.98
Camperdown	56.22	24.53	16.28	3.89	2.74	100.02
Richmond	52.12	29.88	15.00	2.95	2.25	99.89
Baynesfield	48.72	30.29	17.45	2.73	2.00	99.69
Qudeni	39.10	32.18	24.60	2.07	1.39	100.17
Bray Hill	76.87	15.11	5.16	8.64	7.10	99.77
Highmoor	50.04	27.24	19.07	3.12	2.16	100.04
Hawkestone	59.86	26.27	10.58	3.87	3.08	100.08
Ixopo	50.70	27.56	19.21	3.12	2.17	100.00
Knight	60.80	25.49	11.70	4.06	3.14	100.13
Westfield	55.97	27.96	13.56	3.39	2.60	100.25
Nutfield	59.31	25.92	12.26	3.89	2.99	100.23
Ntabhamhlope	75.22	15.08	7.76	8.47	6.39	99.76
Inadi	74.09	12.52	7.15	10.05	7.38	99.31
Kranskop	57.78	26.74	13.02	3.67	2.80	99.80
Stac Braes	55.74	23.27	15.36	4.07	2.87	99.85
Springbrook	52.98	26.82	17.60	3.36	2.37	100.17
Linklater	60.23	27.10	10.18	3.77	3.05	99.78
Freeland	82.81	10.85	4.60	12.95	10.21	99.51
Kilmashogue	77.80	12.16	7.68	10.86	7.75	99.63
Lilydale	51.51	26.33	19.27	3.33	2.27	100.18
Inglenook	62.17	23.74	11.27	4.45	3.42	100.13
Mooi River	72.87	11.56	12.33	10.69	6.38	99.37
Glen Eland	56.09	28.62	13.23	3.33	2.57	100.04
Boscombe	56.63	26.00	14.93	3.70	2.71	99.99
The Gem	48.60	27.98	19.76	2.95	2.04	100.18
Cramond	62.16	21.86	13.13	4.82	3.50	99.93
Rambleholm	71.07	13.53	12.31	8.91	5.65	99.69

	MnO (%)	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Cr_2O_3	NiO
Bloemendal	0.09	0.35	0.05	0.10	0.15	1.806	0.15	0.065	0.015
Cedara	0.08	0.31	0.12	0.02	0.29	1.761	0.23	0.070	0.006
Windy Hill	0.02	0.22	0.04	0.07	0.48	0.969	0.08	0.026	0.002
Eston	0.11	0.47	0.13	0.10	0.18	1.496	0.10	0.064	0.020
Harmony	0.06	0.40	0.17	0.16	0.12	1.960	0.16	0.050	0.005
Dargle	0.03	0.40	0.05	0.00	0.85	1.181	0.08	0.024	0.005
Camperdown	0.14	0.59	0.20	0.12	0.27	1.584	0.05	0.033	0.004
Richmond	0.05	0.36	0.05	0.04	0.18	2.015	0.13	0.050	0.008
Baynesfield	0.07	0.46	0.20	0.06	0.43	1.736	0.24	0.031	0.010
Qudeni	0.11	0.86	0.02	0.04	0.15	2.794	0.12	0.164	0.020
Bray Hill	0.03	0.50	0.08	0.09	1.12	0.676	0.11	0.025	0.003
Highmoor	0.06	1.09	0.06	0.01	0.52	1.769	0.10	0.057	0.019
Hawkestone	0.05	0.41	0.07	0.05	1.29	1.386	0.09	0.027	0.003
Ixopo	0.05	0.39	0.01	0.02	0.27	1.579	0.14	0.068	0.007
Knight	0.14	0.34	0.03	0.02	0.25	1.222	0.09	0.034	0.014
Westfield	0.07	0.34	0.09	0.00	0.27	1.861	0.08	0.044	0.010
Nutfield	0.04	0.34	0.03	0.02	0.44	1.700	0.10	0.048	0.010
Ntabhamhlope	0.03	0.23	0.03	0.00	0.24	1.075	0.08	0.021	0.003
Inadi	0.11	0.83	1.43	0.27	1.49	1.263	0.12	0.035	0.004
Kranskop	0.17	0.33	0.01	0.01	0.37	1.209	0.10	0.050	0.013
Stae Braes	0.27	1.11	1.07	0.48	0.88	1.516	0.09	0.047	0.011
Springbrook	0.05	0.41	0.09	0.12	0.43	1.470	0.14	0.056	0.007
Linklater	0.10	0.39	0.03	0.00	0.48	1.228	0.06	0.009	0.006
Freeland	0.02	0.23	0.06	0.05	0.20	0.606	0.06	0.020	0.000
Kilmashogue	0.02	0.28	0.07	0.04	0.55	0.928	0.07	0.021	0.002
Lilydale	0.08	0.50	0.07	0.05	0.18	1.945	0.11	0.115	0.017
Inglenook	0.05	0.42	0.09	0.06	0.62	1.557	0.11	0.033	0.005
Mooi River	0.11	0.23	0.09	0.07	0.66	1.314	0.08	0.055	0.006
Glen Eland	0.04	0.26	0.02	0.03	0.09	1.528	0.07	0.054	0.006
Boscombe	0.05	0.19	0.01	0.00	0.16	1.880	0.06	0.063	0.008
The Gem	0.07	0.48	0.03	0.10	0.33	2.537	0.13	0.128	0.033
Cramond	0.05	0.38	0.11	0.16	0.23	1.686	0.10	0.055	0.007
Rambleholm	0.07	0.28	0.10	0.04	0.12	2.019	0.09	0.058	0.007

Average chemical analyses for the three main parent materials of this data set were derived from data provided in "Analyses of Rocks, Minerals and Ores" (1964), and are also expressed in terms of oxide percent of the non-volatile material:

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SiO_2/Al_2O_3	SiO_2/R_2O_3
Dolerite	51.87	15.29	10.45	1.36	5.77	4.02
Sandstone	81.14	8.83	3.37	0.47	15.62	12.56
Shale	64.58	14.23	12.77	0.86	7.72	4.91

MacVicar (1965) reports similar figures for dolerite from the Tugela basin.

Derived indices:

	$\frac{SiO_2/Al_2O_{3\cdot soil}}{SiO_2/Al_2O_{3\cdot rock}}$	$\frac{SiO_2/R_2O_{3\cdot soil}}{SiO_2/R_2O_{3\cdot rock}}$	$\frac{TiO_{2\cdot soil}}{TiO_{2\cdot rock}}$
Bloemendal	0.36	0.37	2.10
Cedara	0.47	0.46	1.29
Windy Hill	0.52	0.51	2.06
Eston	0.34	0.40	1.10
Harmony	0.94	0.68	1.69
Dargle	0.65	0.81	0.87
Camperdown	0.25	0.22	3.37
Richmond	0.51	0.56	2.34
Baynesfield	0.47	0.50	2.02
Qudeni	0.13	0.11	5.94
Bray Hill	0.55	0.57	1.44
Highmoor	0.20	0.17	3.76
Hawkestone	0.67	0.77	1.61
Ixopo	0.54	0.54	1.84
Knight	0.52	0.64	0.90
Westfield	0.44	0.53	1.37
Nutfield	0.67	0.74	1.98
Ntabhamhlope	0.54	0.51	2.29
Inadi	1.30	1.50	0.93
Kranskop	0.64	0.70	1.41
Stae Braes	0.71	0.71	1.76
Springbrook	0.58	0.59	1.71
Linklater	0.65	0.76	1.43
Freeland	0.83	0.81	2.61
Kilmashogue	0.70	0.62	1.29
Lilydale	0.43	0.46	1.43
Inglenook	0.58	0.70	1.14
Mooi River	1.38	1.30	0.97
Glen Eland	0.21	0.20	3.25
Boscombe	0.64	0.67	2.19
The Gem	0.38	0.42	1.87
Cramond	0.84	0.87	1.96
Rambleholm	1.15	1.15	1.48

XRF data recalculated for the clay fraction (< 0.002mm) on the assumption that sand + silt fraction is essentially quartz (SiO_2).

Sample	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SiO_2/ Al_2O_3	SiO_2/ R_2O_3	SiO_2/Al_2O_3 (clay/rock)	SiO_2/R_2O_3 (clay/rock)
Bloemendal	23.42	44.25	28.61	0.90	0.64	0.117	0.130
Cedara	16.00	39.86	39.46	0.68	0.42	0.118	0.104
Windy Hill	39.03	39.18	16.68	1.69	1.33	0.108	0.106
Eston	43.40	33.90	19.71	2.18	1.59	0.378	0.396
Harmony	34.54	35.03	26.27	1.68	1.13	0.218	0.230
Dargle	37.84	40.42	16.93	1.59	1.26	0.276	0.313
Camperdown	43.14	31.86	21.14	2.30	1.62	0.147	0.129
Richmond	26.34	45.97	23.08	0.97	0.74	0.126	0.151
Baynesfield	29.75	41.49	23.90	1.22	0.89	0.158	0.181
Qudeni	-3.22	54.54	41.69	-0.10	-0.07	-0.006	-0.006
Bray Hill	49.72	32.85	11.22	2.57	2.11	0.165	0.168
Highmoor	19.42	43.94	30.76	0.75	0.52	0.048	0.041
Hawkestone	27.02	47.76	19.24	0.96	0.77	0.124	0.157
Ixopo	26.42	41.13	28.67	1.09	0.76	0.141	0.155
Knight	35.74	41.79	19.18	1.45	1.12	0.251	0.279
Westfield	31.20	43.69	21.19	1.21	0.93	0.210	0.231
Nutfield	33.30	42.49	20.10	1.33	1.02	0.172	0.208
Ntabhamhlope	43.68	34.27	17.64	2.17	1.63	0.139	0.130
Inadi	25.97	35.77	20.43	1.23	0.90	0.213	0.224
Kranskop	35.05	41.14	20.03	1.45	1.11	0.188	0.226
Stac Braes	43.26	29.83	19.69	2.47	1.74	0.320	0.354
Springbrook	36.46	36.24	23.78	1.71	1.21	0.222	0.246
Linklater	28.98	48.39	18.18	1.02	0.82	0.132	0.167
Freeland	57.03	27.13	11.50	3.57	2.81	0.229	0.224
Kilmashogue	50.67	27.02	17.07	3.19	2.27	0.204	0.181
Lilydale	32.65	36.57	26.76	1.52	1.03	0.263	0.256
Inglenook	43.54	35.43	16.82	2.09	1.60	0.362	0.398
Mooi River	35.40	27.52	29.36	2.19	1.30	0.380	0.323
Glen Eland	33.47	43.36	20.05	1.31	1.01	0.084	0.080
Boscombe	11.49	53.06	30.47	0.37	0.27	0.048	0.055
The Gem	34.94	35.42	25.01	1.68	1.16	0.291	0.289
Cramond	33.61	38.35	23.04	1.49	1.08	0.193	0.220
Rambleholm	35.71	30.07	27.36	2.02	1.28	0.350	0.318