SITE RELATIONSHIPS FOR PINUS PATULA

IN THE EASTERN TRANSVAAL ESCARPMENT

AREA

by

CHRISTOPHER JOHN SCHUTZ

B.Sc For. (Stellenbosch)

Hons. B.Sc For. (Stellenbosch)

Submitted in partial fulfilment

of the requirements for

the degree of

DOCTOR OF PHILOSOPHY

Department of Soil Science and Agrometeorology

University of Natal

PIETERMARITZBURG

MARCH 1990

Frontispiece. Pine plantations on the slopes of Mount Anderson.

DECLARATION

I declare that the results contained in this thesis are from my own original work except where acknowledged.

C.J. SCHUTZ

MARCH 1990

ACKNOWLEDGEMENTS

The assistance of the following persons is gratefully acknowledged:

Professor J.M. de Villiers for guidance, constructive criticism and assistance, as supervisor of this study. To cite but one example, a new dispersion technique for solving the problem of particle size analysis of soils high in manganese oxides.

Dr A.P.G. Schönau for advice as co-supervisor.

The Department of Environment Affairs for authorizing and supporting the study. Dr H.A. Lückhoff, Director of the S.A. Forestry Research Institute at the time this study commenced, gave enthusiastic support.

My colleagues Mr T.J. Hodgson, Professors D.G.M. Donald, A. van Laar and A. Theron, Dr J.J.N. Lambrechts and Dr W.K. Darrow for advice in the planning stages.

Mr G.N. Schafer and his team of assistants for much of the field work, which they executed with great dedication and enthusiasm. Gavin Schafer also took several of the photographs.

Dr L.M. Hodgson for supervising and carrying out many of the soil analyses, and Messrs J. Hunsraj and D. Chanderbally for particle size analyses.

Mr A.C. Döhne for assistance with laboratory work, checking data in the field and for laying out the model validation plots.

Dr C.P. Kromhout for advice in planning the study on wood properties, Mr P.A. Kirkman and his assistants for analysing the thousands of wood samples, and Mrs S.T. Coetzee for recording the anatomical characteristics of stem bumps and affected timber. Mr J.E. Kietzka for analyses of variance of wood properties.

Dr B.V. Bredenkamp for advice on mensurational problems and assistance with computer programmes, in particular the writing of a programme to compute DRIS indices.

Professor A.A. Rayner, Dr J.S. Galpin and Dr D.C. Grey for advice on regression analysis. Dr Grey also assisted with principal components and factor analyses. Dr G. van Wyk for advice on computer usage and statistical problems as well as encouragement throughout the study. Mr N.C. Loveday for solving computer problems, and Mrs R. Falkenhagen for manipulation of data sets.

Messrs C.J.S. Venter, N. Sheik, P. Ramcharan, P. Mkhize, E. Abdullah and M. Segage for data entry, dark room work and drafting of diagrams and maps.

Mr H. Haigh for taking over many of my duties to enable me to devote more time to this study.

Mondi Forests, Ltd for permission to sample sites and stands on their forest estate.

Mrs C. Perold and Miss L. Steenkamp for typing the initial drafts and Miss S. de Jager for typing the final draft.

My family, for sufferance.

Any others whose names I might inadvertently have ommitted.

Finally I wish to thank the good Lord, for revealing some of the knowledge of His creation and for solving numerous problems with this study.

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ABSTRACT

The largest area of commercial timber plantations in southern Africa is situated along the Eastern Transvaal Drakensberg Escarpment north of Nelspruit. The site requirements of tree species in this area are poorly understood. The purpose of this study was to examine site-tree relationships in the region and the implications of such relationships for the science of forestry. *Pinus patula* Schiede & Deppe in Schlecht. & Cham. was selected for the study as it is the most widely planted species in the region.

In Chapter 1 the geology, geomorphology, climate, soils and vegetation of the study area are described. A geological map was compiled. Soil descriptions were based on 439 soil pits distributed so as to cover the range of site conditions in the area.

The regression techniques used to identify key environmental factors and to model their relationships with tree parameters are described in Chapter 2, in which site-growth relationships specifically are investigated. In mature stands of *P. patula* 159 plots were established in such a way as to cover the widest variation in both site conditions and tree growth. The relationship between *site index* (mean top height at 20 years) and 100 site plus 10 stand parameters recorded at each plot was modelled by means of best-subsets, multiple and ridge regression. Several candidate models were compared on the basis of coefficient of determination and validation using independent data. The best model predicted the *site index* of the validation plots within 60 cm of the measured *site index*. The possible roles of the site variables identified by the models are discussed.

In Chapter 3 site-foliar nutrient relationships are described. A close relationship was found between foliar and soil nutrient levels for the six major geological substrates. *Site index* was more accurately predicted from concentrations of individual foliar nutrients than from ratios of these nutrients. The Diagnosis and Recommendation Integrated System (DRIS), however, appeared to have greater potential for nutrient diagnosis. Provisional DRIS norms for *P. patula* were computed.

In Chapter 4 the excessive accumulation of litter in *P. patula* stands was examined. Undecomposed litter layers were greater than 15 cm in thickness on nearly 25% of the 159 sites studied. Average litter layers contained greater amounts of nutrients than the underlying topsoil. Due to the colonization of

the litter by tree roots, the degree of immobilization of nutrients in litter is not known. Environmental factors associated with variation in litter thickness were identified by models which explained up to 73% of the total variation. These factors are considered to act indirectly by promoting or retarding decay organisms. The possible implications of litter accumulation for the maintenance of site productivity are discussed.

In Chapter 5 relationships between site and some wood properties are described. Although between-tree variation was larger than between-site variation, some important relationships with site were identified. 10% of all trees on the 159 plots had severe stem bumps. Most of the variables in a model to predict the severity of bumps could be interpreted as being associated with stem stability or exposure. The conclusion was that wind is probably the major cause of this defect.

The findings of the study are summarized in Chapter 6. Particular attention is given to a synthesis of the possible roles of site factors in their relationships with the tree parameters investigated. There were strong relationships between tree parameters and mainly *rainfall*, *altitude*, *soil wetness*, *exchangeable bases*, *effective rooting depth*, *slope position* and *geology*. The single most deficient nutrient element appeared to be *calcium*. The implications for both research and management are outlined.

INTRODUCTION

The Eastern Transvaal Drakensberg Escarpment area north of Nelspruit, between 24°31′ and 25°22′S, 30°25′ and 31°02′E, comprises the largest contiguous block of commercial timber plantations in southern Africa. Until recently it was generally regarded as the largest man-made forest in the world.

Afforestation commenced in 1903 and expanded rapidly until today virtually all available land has been afforested. The boundaries of the region are determined almost solely by rainfall. Within the region, however, afforestation was undertaken with little knowledge of site conditions or site requirements of the species, apart from the need to allocate *Eucalyptus grandis* to the warmer areas. Today the scenario has changed little, the need both to understand and to quantify site-tree relationships being an urgent matter. What makes this requirement particularly important is the decreasing availability of land for afforestation in southern Africa and the consequent need to increase productivity per unit area. A better knowledge of site-tree relationships would facilitate site classification for yield prediction, species choice, site-specific silviculture, nutrition programmes and nutrient cycling problems.

The purpose of this study was therefore to examine site-tree relationships within the region defined above and the implications of such relationships for the science of forestry. There was some urgency that this be done before the disappearance of all first rotation stands, so as to avoid introducing rotation number as a likely additional source of variation.

The three main pine species planted in the area are *Pinus elliottii* Engelm. *var. elliottii* Little & Dorman, *P. patula* Schiede & Deppe in Schlecht. & Cham., and *P. taeda* L. Although preliminary investigations were done on all three species, *P. patula* was regarded as the most suitable for this study as it is the most widely planted species, not only within the study area, but also in the whole of southern Africa (Dept. of Environment Affairs, 1987).

In order to relate tree parameters to site factors, a thorough knowledge of the physical environment within the area concerned is a prerequisite. A description of site was thus a neccessary first step. Secondly, the tree parameters to be related to measured site factors need to be selected. Most site studies have been concerned solely with the prediction of site index from measured site factors (Hägglund, 1981). For a more thorough understanding of site-tree relationships, however, it was considered necessary to examine not only site index, but also foliar nutrients, litter properties and wood properties.

Site description

The selected tree parameters were most likely to be related to factors of the environment determined by geology, geomorphology, climate and soils. A geology map of the southern half of the region had been published, but in spite of the long history of mining activity no map of the northern half existed. Rainfall data were readily available from a network of rain guages within the area, but other climatic information such as temperature data was scant. Soils had not been well described. The land type survey of the region (Schoeman *et al*, 1980) was based on only ten soil profiles. It was therefore necessary to describe particularly the geology and soils in greater detail.

Site index

Analogue methods based on climate (water balance, moisture index, temperature, thermal efficiency and drought occurrence) have mostly been used to determine the commercial forestry potential of unafforested land in South Africa (Grey, 1978). Species are then allocated according to their known climatic requirements. Most of the research in this regard was done by Poynton (1971, 1972, 1979). Attempts to evaluate soil types for their productivity potential according to the South African binomial system of soil classification (Mac Vicar *et al*, 1977) were recently undertaken by Schönau and Fitzpatrick (1981).

These broad, regional classifications, however, give poor predictability when applied to smaller areas of more uniform climatic conditions, as many of the location-specific parameters which influence production are not taken into consideration (Grey, 1978). Some quantitative site studies for small areas have been undertaken in *P. patula* with varying degrees of success (Evans, 1971; Grey, 1978, Schönau and Wilhelmij, 1980), but none of the models obtained were ever tested.

The amount of off-site planting of *P. patula* which has taken place in the Eastern Transvaal study area is ample evidence of the current poor understanding of the site requirements of this species. There is an urgent need for a site classification system based on a sound knowledge of site-growth relationships.

Foliar nutrient variation

Very little research has been done in the field of site index-foliar nutrient relationships in *P. patula*. Foliar nutrient concentrations associated with optimum tree growth would have great value in nutrient diagnosis and fertilizer research, particularly if they could be expressed as DRIS (Diagnosis and Recommendation Integrated System) norms. DRIS (Beaufils, 1973) has so far received scant attention in world forestry and not at all in *P. patula* (Schutz and De Villiers, 1988). A study of foliar nutrient variation would also assist in the indentification of deficiencies, toxicities or possible nutrient cycling problems.

Litter properties

Abnormally thick litter layers in *P. patula* stands have been found to adversely affect the productivity of successive rotations in Swaziland (Morris, 1986). The fact that undecomposed litter layers in the Eastern Transvaal tend to be thicker than those in Swaziland points to the need for research into litter properties and their relationships with site. This could help to identify the possible causes of litter accumulation and its effect on nutrient cycling.

Wood properties

In relation to site, wood density of *P. patula* has nowhere been intensively studied, while spirality has been virtually ignored world-wide for all species, yet these properties are of great importance in determining wood quality. The purpose of this part of the study was to determine whether any variation in these properties can be attributed to site, and if so, whether this variation would be large enough to have implications for yield prediction, species choice or tree improvement programmes. In addition causes were sought for the phenomenon of "stem bumps" development in *P. patula*, a common wood defect in the study area.

Methods

Relationships between site and tree parameters were investigated by means of modelling techniques. A description of the site parameters and the regression procedures used is given in Chapter 2.

CHAPTER 1

SITE DESCRIPTION

1.1 LOCALITY AND LANDUSE

1.1.1 GENERAL

The study area comprises the largest contiguous block of commercial timber plantations in Southern Africa, lying between 24°31′ and 25°22′ south latitude, and 30°25′ and 31°02′ east longitude (Fig. 1.1). The plantations stretch northwards from the Crocodile River near Nelspruit, along the Eastern Transvaal Drakensberg Escarpment and as far as Mariepskop near Hoedspruit. The forestry area is nearly 100 km long and 50 km wide at its widest point (Fig. 1.2). Most of the area lies within the Pilgrim's Rest magisterial district, but portions of the White River, Nelspruit and Lydenburg magisterial districts are also included. The main towns within the area are Sabie, Graskop, Pilgrim's Rest and White River. Railway branch-lines run from Nelspruit through Sabie to Graskop and from Nelspruit to White River. The area is well served by a network of all-weather roads.

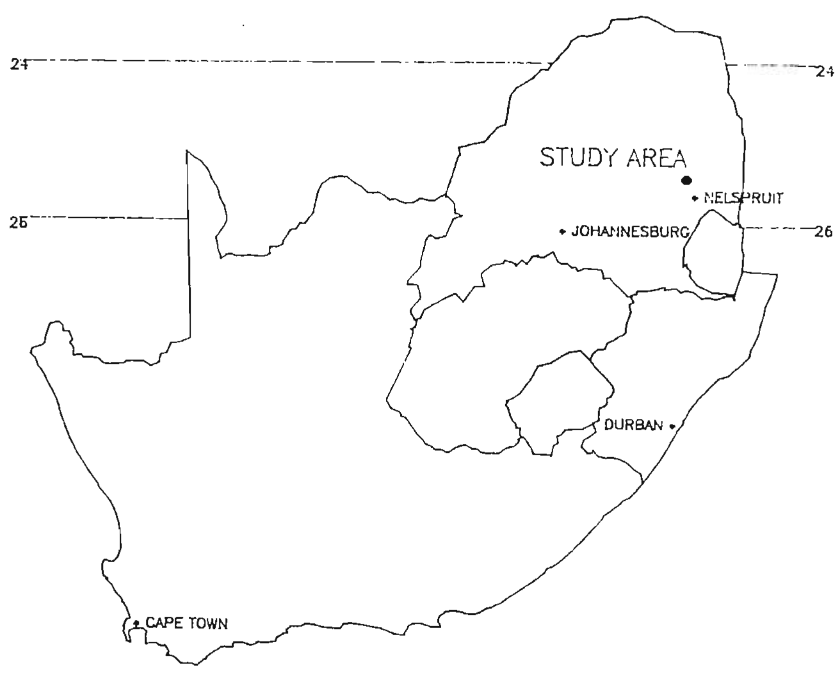


Figure 1.1 Location of study area

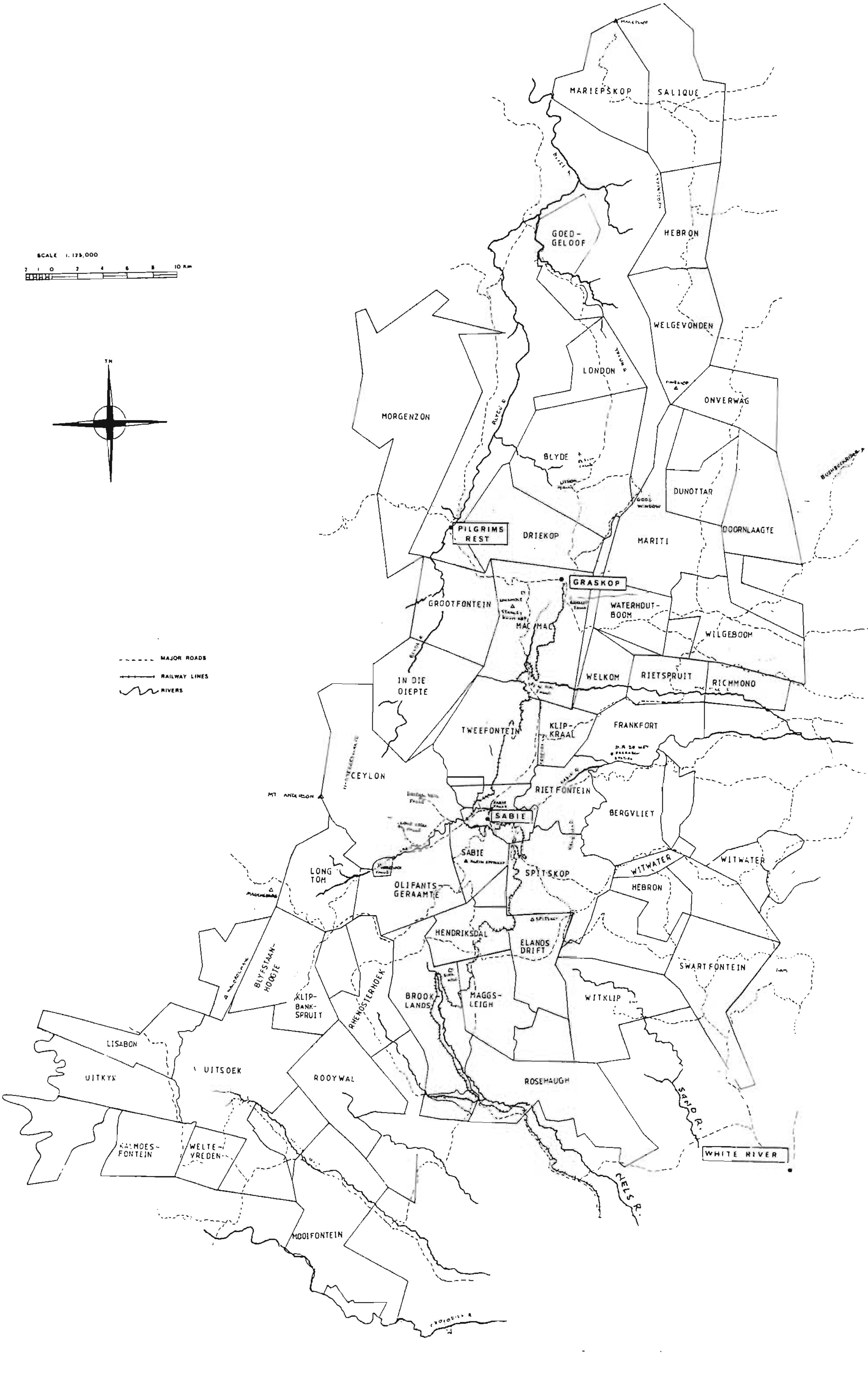


Figure 1.2 Major plantations of the Sabie area

The region owed its early development to gold, which was discovered in 1972, but there are signs of gold-diggings dating from even earlier times. For 75 years gold mining was the most important industry, until the largest mines closed in the 1950's. The recent increase in the price of gold, however, has resulted in a small-scale resumption of mining operations.

Due to the high rainfall, leached soil and steepness of the terrain, the area is of limited agricultural potential. Citrus and sub-tropical fruits are, however, grown extensively in the better agricultural environment east and south of the forestry zone, while mixed farming is practised in the lower rainfall areas of the west and north. Tourists are attracted in ever-increasing numbers by the spectacular scenery of the area. There are several nature reserves, routes of the National Hikingway System, trout fishing opportunities and numerous resorts.

1.1.2 FORESTRY

Even before the discovery of gold, an enterprising settler, J. Brooke Shires, planted the first small commercial eucalypt and wattle plantation at Brooklands. As the indigenous forests were unable to supply the demand for timber by the mines, the Transvaal Gold Mining Estates Co. (T.G.M.E.) planted its first wattle and eucalypt plantations in 1903 at Graskop. The first pines were planted by the Department of Forestry in 1906, also near Graskop, and TGME soon followed suit. In 1929 the Department of Forestry began its campaign of afforestation to provide employment for whites in the depression years, and forestry expanded rapidly. By 1948 TGME's profits from forestry exceeded those from mining and a separate company, S.A. Forest Investments Ltd (now Mondi Forests), was created. (With acknowledgments to Sabie Forestry Museum.)

Forestry is by far the largest industry and employer in the area, virtually all afforestable land having been planted up. The major growers are the State and Mondi Forests, followed by Hunt, Leuchars and Hepburn (HL & H), Sappi Forests and smaller growers. Plantation areas are shown in Table 1.1. *P. patula* is the most widely-planted species in the area. Pines are grown mostly for sawtimber (94% of the area). During 1986, 955 181 m^3 of sawlogs, 334 490 tonnes of pulpwood and 325 597 t of mining timber were produced from the Pilgrim's Rest magisterial district alone (Dept. of Environment Affairs records). Pulpwood is processed at a mill close to the area, but most other timber is processed by at least 30 wood-using industries within the area.

Table 1.1 Plantation areas (to the nearest 1000 ha) for the Escarpment forestry zone north of Nelspruit (Source: Unpublished records of the Dept. of Environment Affairs and plantation owners, 1986/87).

P. patula	57 000
P. elliottii	36 000
P. taeda	27 000
Total	120 000
Eucalypts (mainly *E. grandis*)	47 000
Others species	3 000
Total	50 000
Total all species	170 000
State ownership	88 000
Private ownership	82 000
Total	170 000

1.2 GEOLOGY

The attention of geologists has been focussed on the area ever since the discovery of gold in the last century and other minerals subsequently. A major geological survey resulted in the publication of a map of the area south of Sabie in 1960 (Visser and Verwoerd, 1960). Since then surveys and lithostratigraphic studies have been undertaken on the Transvaal Supergroup (Zietsman, 1964; Button, 1973a), the Wolkberg Group (Button, 1973b), the Malmani Subgroup (Button, 1973c), the Timeball Hill Formation (Eriksson, 1973) and the Archaean granite basement (Robb, 1978; Lageat and Robb, 1984). A great deal of confusion surrounding the lithostratigraphy of the area was cleared up by the recent handbook published by the Geological Survey (South African Committee for Stratigraphy (SACS), 1980). The whole Escarpment region forms the eastern rim of the saucer-shaped Bushveld Igneous Complex of the central Transvaal. The stratigraphy and lithology are shown in Table 1.2. With the aid of the published geological map of the southern part of the area (Visser and Verwoerd, 1960), the unpublished map by Zietsman (1964) and various sketch maps supplied by the Geological Survey, augmented by information obtained during the course of the field survey undertaken for this study, a geological map at a scale of 1: 125 000 was compiled. The map shows the geological formations judged to be of importance for forestry purposes. A photo-reduction is shown in Fig. 1.3, with a plantation overlay. It will be seen that the formations run roughly parallel with the Drakensberg Escarpment in a N.N.E.-S.S.W. direction.

The major rock types are shown in a cross-section of the geology in Fig. 1.4. The afforested area overlies essentially four major lithostratigraphic groups, which are in turn intruded by a network of diabase dykes and sills. The lowveld comprises the Nelspruit granite. The three groups deposited over the granite basement are collectively known as the Transvaal Sequence. They comprise the Wolkberg Group of the Drakensberg Escarpment, over which lies the Chuniespoort Group, followed by the high mountain ranges of the Pretoria Group. The strata of the Transvaal Sequence all dip westwards (Fig. 1.4). The descriptions below were compiled from Button (1973a, b and c), Eriksson (1973), Lageat and Robb (1984), Robb (1978), SACS (1980) and Zietsman (1964), with interpolations from personal observation.

Table 1.2. Stratigraphy and lithology of the Escarpment area between Nelspruit and Mariepskop (Adapted from SACS 1980)

CHRONOSTRATIGRAPHY		LITHOSTRATIGRAPHY			LITHOLOGY	THICKNESS (m)
Age (Ma)	Erathem	Group	Formation	Member		
	Mokolian				Diabase intrusions	
+2200	Vaalian	Pretoria	Hekpoort Andesite		Andesite, quartzite, shale	0 - 200
			Boshoek		Siltstone, shale, qtzt conglomerate, pyroclastics	0 - 90
			Timeball Hill	Klapperkop Qtzt Klapperkop Qtzt	Shale Quartzite Shale Quartzite Shale	900-1600
			Rooihoogte	Bevet's conglomerate	Quartzite, conglomerate	0 - 50
		Chuniespoort (Malmani Subgroup)	Frisco		Chert-free dolomite	300
			Eccles		Chert-rich dolomite	300
			Lyttelton		Chert-free dolomite	120
			Monte Christo		Chert-rich dolomite	200
			Oaktree		Shale, dark dolomite, Quartzite	10
+2450		Wolkberg	Black Reef		Quartzite, sandstone minor shale, conglomerate	0 - 100
			Sadowa		Shale, quartzite	0 - 50
			Mabin		Felspathic quartzite, mudstone	0 - 100
			Selati		Shale, quartzite	0 - 400
			Abel Erasmus		Basalt, quartzite, shale, chert	0 - 100
			Sekororo		Arkose, shale, quartzite	0 - 240
±2600			Godwan		Lava, tuff, conglomerate quartzite, shale	60
±3000	Swazian				Nelspruit granite	

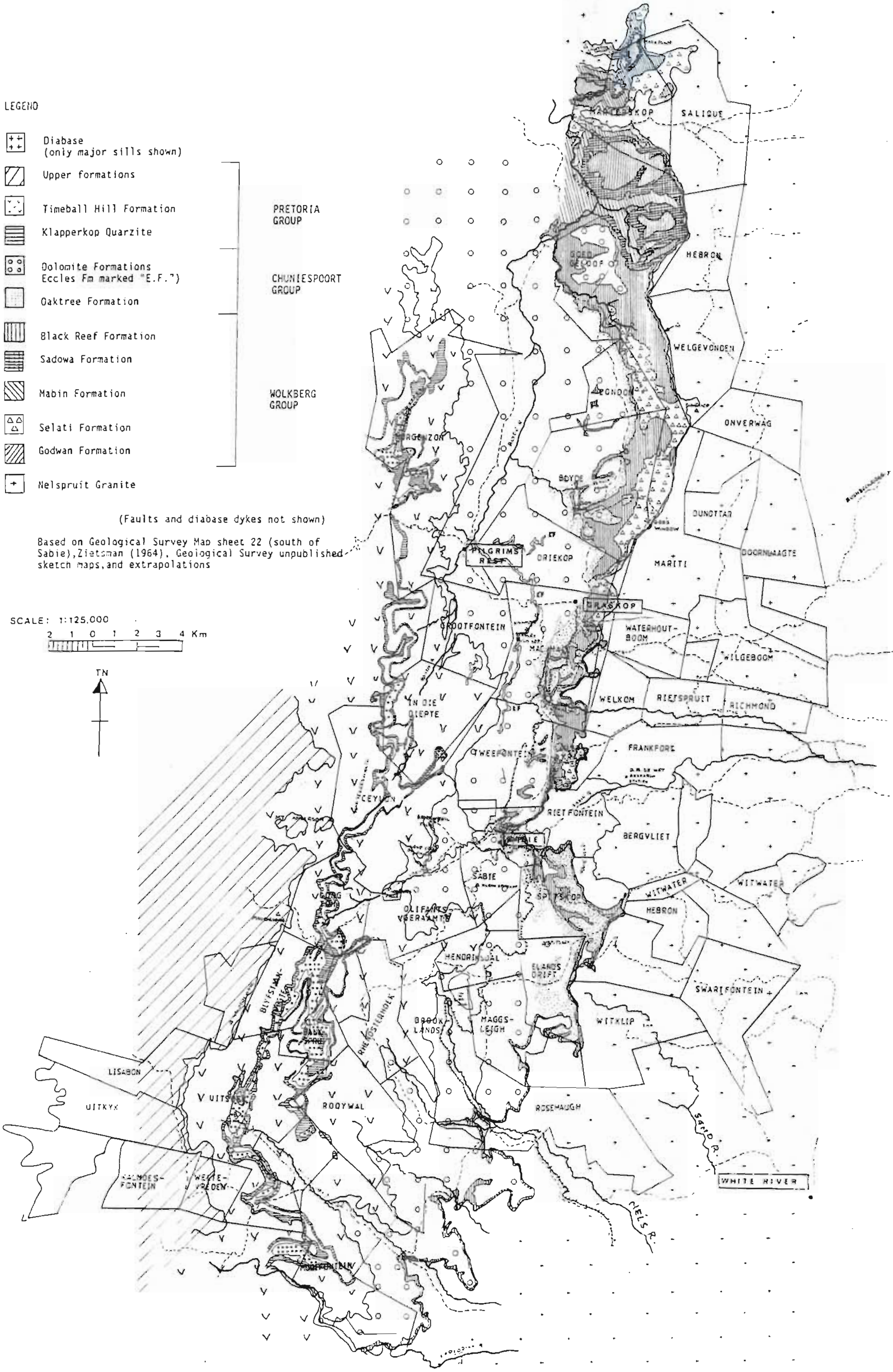


Figure 1.3 Geological formations of the Sabie area

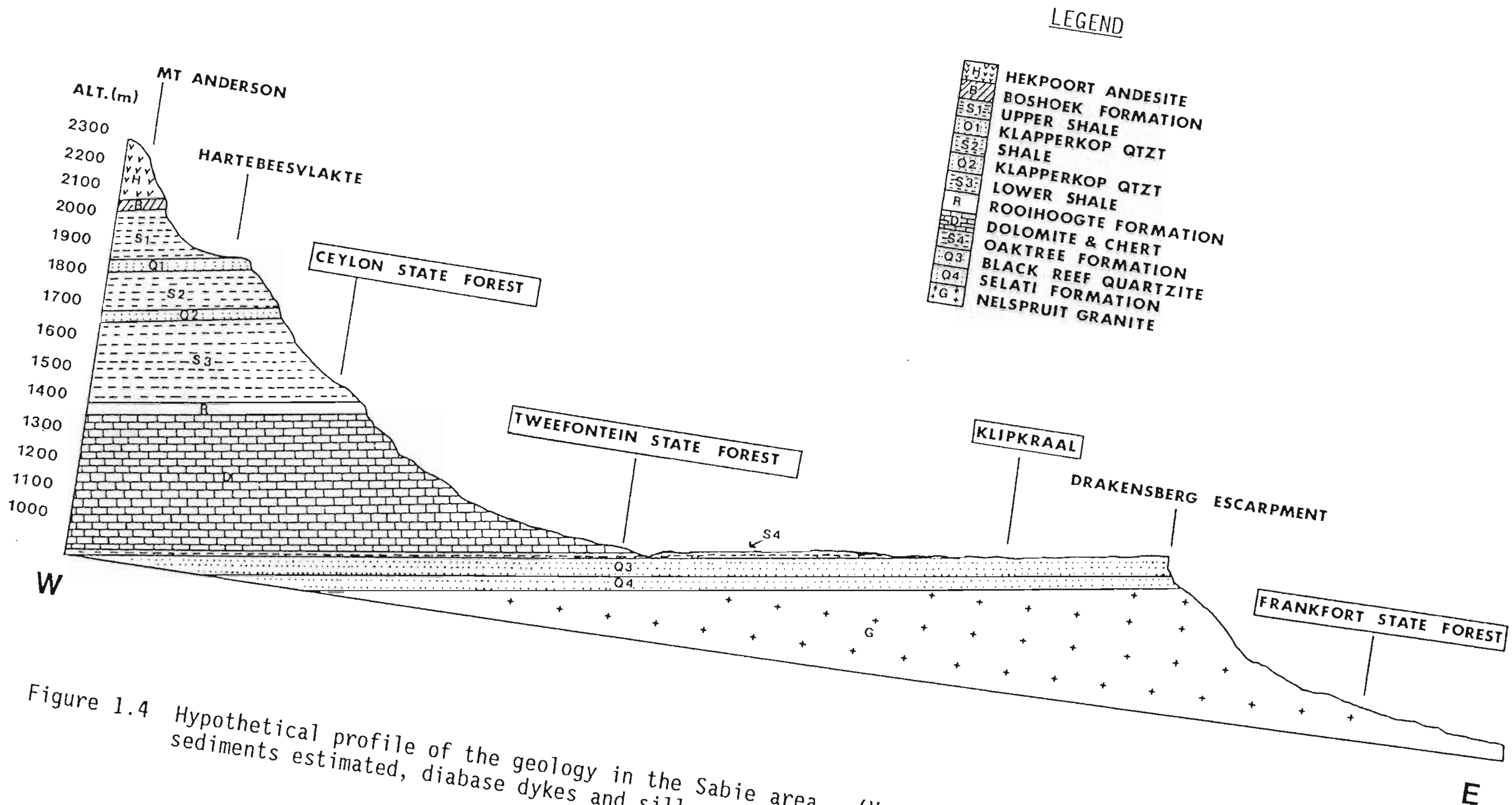


Figure 1.4 Hypothetical profile of the geology in the Sabie area. (Vertical scale exaggerated, dip of the sediments estimated, diabase dykes and sills not shown). Compiled from references listed ...

1.2.1 THE NELSPRUIT GRANITE

The Nelspruit Granite comprises mainly biotite-bearing gneissose granite, i.e. metamorphosed granite which has been remineralized and is similar to a gneiss in structure, but not chemically altered enough to be classified as gneiss (SACS, 1980). This granite is approximately 3000 million years old and is therefore part of the Archaean Eon, generally called the "basement complex" (Lageat and Robb, 1984).

Six granite types have been distinguished by Robb (1978). Most of the afforested area overlies the Nelspruit Porphyritic Granite type. This is a massive, coarse-grained, grey to pink rock characterized by the almost ubiquitous presence of large microcline phenocrysts 10 to 20 mm in length, resulting from the very slow cooling of the granite. It consists mainly of microcline, plagioclase, quartz and biotite, with an unusually wide range in chemical composition (Robb, 1978). Cunning Moor Tonalite is a different type of granite occurring in the north (Welgevonden, Hebron and Salique plantations). It is a massive, medium to coarse-grained rock with a generally equigranular texture. It consists of plagioclase and quartz with lesser amounts of microcline and biotite.

Exposed granite outcrops are visible throughout the area (Fig. 1.5).

1.2.2 THE WOLKBERG GROUP

The Wolkberg Group is prominent in the form of the cliff line comprising the Drakensberg Escarpment. South of Sabie it consists of only one formation, the Black Reef Formation. It is less prominent than in the north, where it increases both in thickness and in the number of formations which make up the alternating layers of quartzite cliffs and steep, grassy slopes of weathered shales. It rests unconformably on the Nelspruit Granite. Within the study area there are seven formations which make up the Wolkberg Group.

1.2.2.1 Godwan Formation

The Godwan Formation is not strictly part of the Wolkberg Group, but is described here as it grades into the Sekororo Formation of the Wolkberg Group north of Sabie. It is not a prominent formation, with virtually no role in geomorphology or soil formation. It is found only near Sabie, where it rests unconformably on the Nelspruit Granite. It is overlain unconformably by the Black Reef Formation as the other formations of the Wolkberg Group are absent from Sabie southwards. Three members are distinguished but seldom exposed.

The Godwan Formation comprises lava, tuff, conglomerate (Fig. 1.6), felspathic quartzite and shale. (Visser and Verwoerd, 1960; P. Smit, Geological Survey, pers. comm.)

1.2.2.2 Sekororo Formation

This formation is found only north of Sabie. It is seldom exposed, but is visible at Kowyn's Pass below Graskop, where it rests unconformably on the granite basement. It comprises arkose, shale, sericitic quartzite, subgraywacke and conglomerate. It is of little importance for forestry.

1.2.2.3 Abel Erasmus Formation

The basaltic lava, quartzite and dolomitic shale of the Abel Erasmus volcanics are not prominent within the area, occurring only north of Sabie. It is of little importance for forestry.

1.2.2.4 Selati Formation

The Selati Formation is composed of a mixed suite of sediments, which includes rapidly alternating beds of shale, argillaceous quartzite and quartzite. South of Sabie the formation has been eliminated by pre-Black Reef erosion, but just north of Sabie it appears as a thin band, thickening rapidly towards Graskop and further north (Figs. 1.7, 1.8). Button (1973b) distinguishes the Anlage, Manoutsa and Mametjas Members. The Manoutsa Member forms a prominent quartzite cliff. (The S.A. Committee for Stratigraphy has not yet accepted this subdivision).

1.2.2.5 Mabin Formation

The Mabin Formation, composed largely of quartzite and felspathic quartzite, is usually encountered a short distance below the Black Reef Formation, from which it is separated by a thickness of dominantly shaly material. It occurs

Figure 1.5 Granite dome on Witklip State Forest (S.F.). Flat summit upper left formed by Black Reef Formation (Fm).

Figure 1.6 Godwan conglomerate, near Sabie.

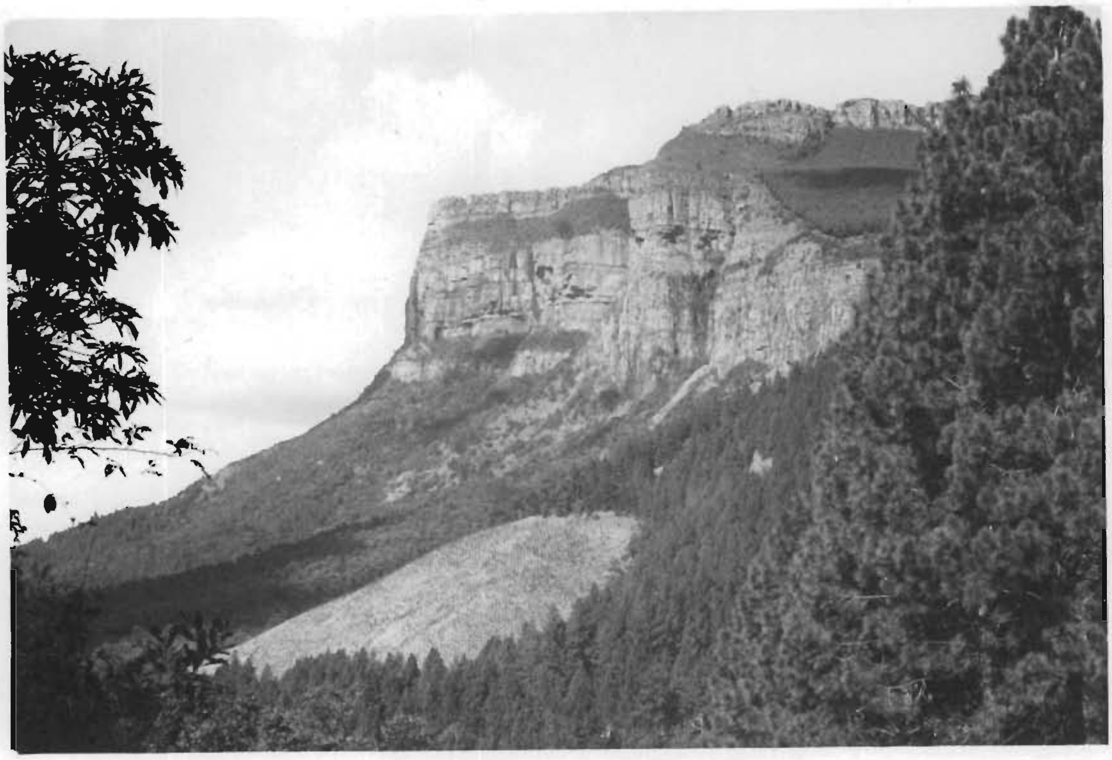


Figure 1.7 Hebronsberg, Mariepskop Plantation (Ptn). The Selati Fm forms the lower step of the main cliff, which is Mabin qtzt. The Sadowa shale separates the Mabin qtzt from the Black Reef qtzt at summit.

Figure 1.8 Visierkop, Welgevonden Ptn. Nelspruit granite lower left, and Selati qtzt above.

only north of Visierkop (Welgevonden Plantation) reaching over 100 m in thickness near Mariepskop (Fig. 1.7).

1.2.2.6 **Sadowa Formation**

The Sadowa Formation, which consists predominantly of shale with interbedded argillaceous quartzite, is sandwiched between the Mabin and Black Reef quartzites (Fig. 1.7).

1.2.2.7 **Black Reef Formation**

The Black Reef Formation is the most prominent feature of the Drakensberg Escarpment, due to its resistance to weathering. It is white to light blue-grey in colour except when ferruginized (e.g. at Sabie). It is a hard, mature, trough cross-bedded quartzite of medium grain size. The topmost few centimetres often consist of grit or small-pebble conglomerate. It rarely exceeds 10 m in thickness south of Sabie, but reaches nearly 100 m near Mariepskop (Figs. 1.9, 1.10). Contact relations with the underlying rocks are unconformable where the Wolkberg Group is absent, conformable where present. The Black Reef Formation has a westerly dip of about 5°.

1.2.3 THE CHUNIESPOORT GROUP

Sediments including dolomite, limestone, chert and shale form the Chuniespoort Group, conformably overlying the Black Reef Formation. Only the Malmani Subgroup is represented in the study area, comprising five formations separated mainly on the basis of chert content.

The dolomite is mostly fine-grained and blue-grey in colour with a black weathered surface (due to manganese oxides) and a wrinkled texture resembling the skin of an elephant in appearance, thus deriving the name "Olifantsklip" (Fig. 1.11). Sometimes an intercalation of layers of pale to dark coloured chert occurs within the dolomite, producing a sandwich appearance known as "bread and butter dolomite" (Fig. 1.12). Dolomite is composed of calcium and magnesium carbonates with additions of manganese, iron and silicon, and traces of lead and zinc. The higher the maganese and iron content of the dolomite, the darker its colour. Solution and removal of dolomite by ground and surface water have resulted in thick residues of black manganese wad, sometimes

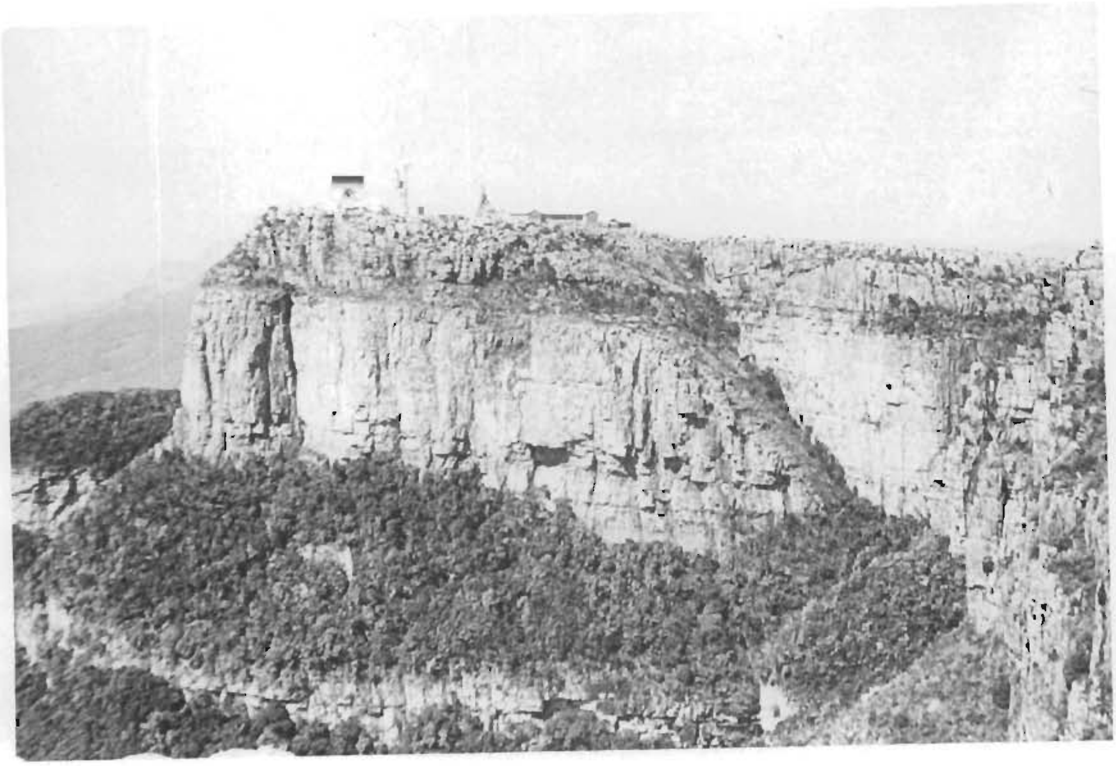


Figure 1.9 Summit of Mariepskop. Black Reef qtzt.

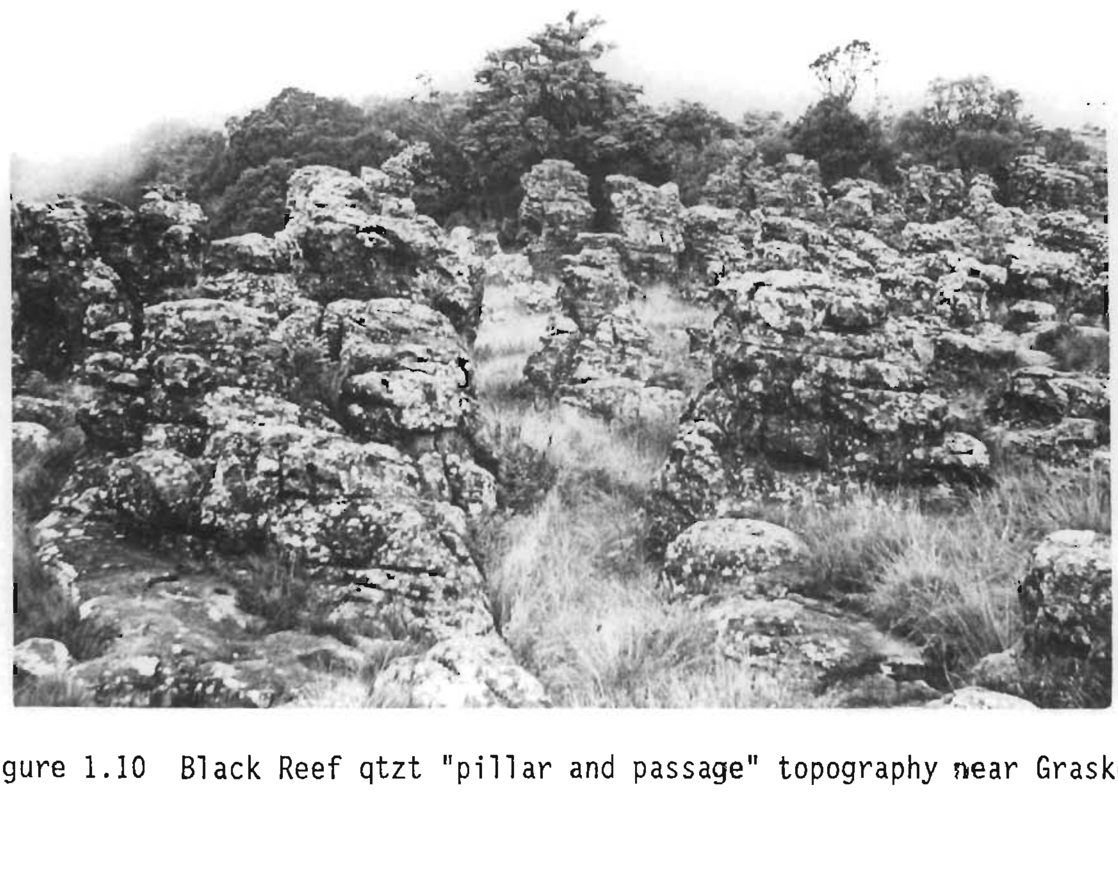


Figure 1.10 Black Reef qtzt "pillar and passage" topography near Graskop.

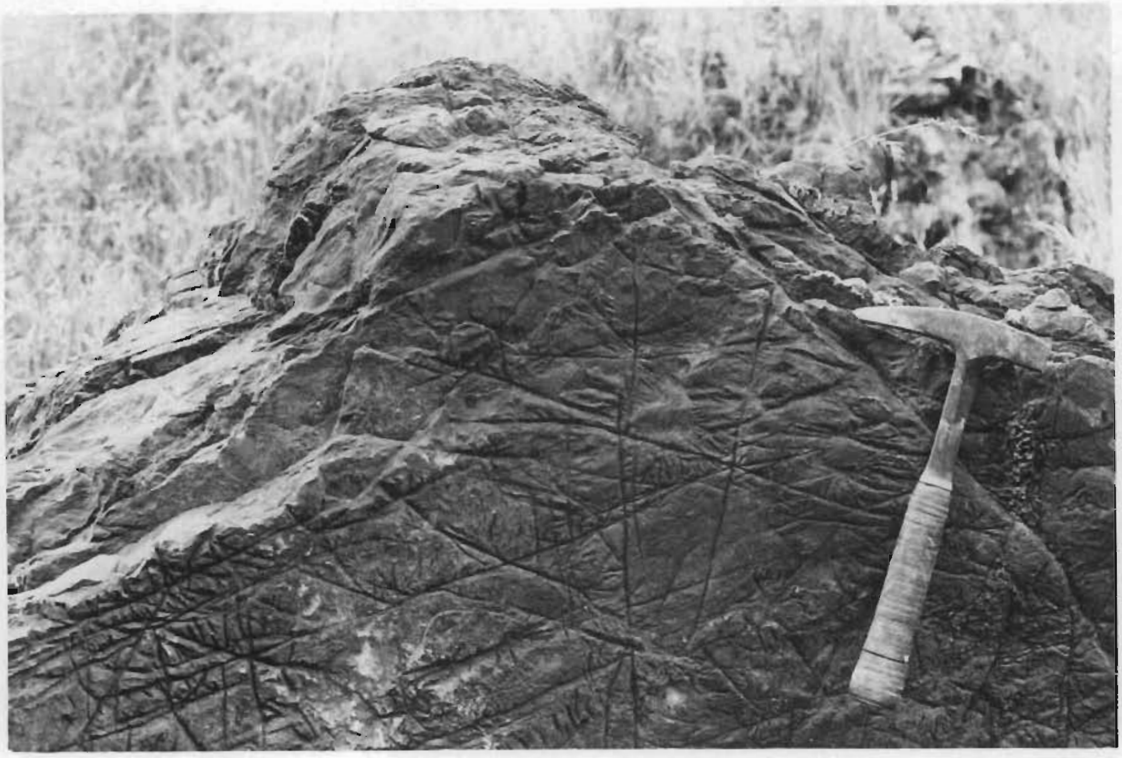


Figure 1.11 "Olifantsklip" dolomite.

Figure 1.12 "Bread and butter" dolomite.

containing as much as 25% MnO_2. Lenses of high grade pyrolusite have been mined from time to time.

1.2.3.1 Oaktree Formation

Formerly known as the "transitional shales", the Oaktree Formation has in the past been grouped with the Black Reef Quartzites, then the Dolomite Series and at present with the Chuniespoort Group. It comprises beds of black carbonaceous mudstone and shale (weathering to a characteristic pale yellow colour), a dark coloured dolomite (high in manganese and iron) with little chert, and some quartzite. Ripple marking on bedding surfaces is the only sedimentary structure of note. It is usually less than 10 m thick, and disappears in the south.

1.2.3.2 Monte Christo Formation

The Monte Christo Formation is characterized by an abundance of chert. The dolomite is generally light grey in colour, but white where recrystallized. The chert is present in layers, usually dark grey to black, but on weathering it bleaches white. Beds of black carbonaceous mudstone are common. South of Sabie a bed of chert-in-shale breccia occurs. Various mechanical sedimentary structures are found. The formation is about 200 m thick in this area.

1.2.3.3 Lyttelton Formation

This is a chert-poor zone with dark coloured, fine-grained, crystalline dolomite. Sedimentary structures are abundant. Particularly diagnostic of this zone are a class of elongated mega-domes, examples of which can be seen in the cutting at the highest point of the road between Rosehaugh and Sudwala. The width of the formation is a fairly constant 120 m.

1.2.3.4 Eccles Formation

This is a chert-rich zone, which is sometimes present in "bread and butter" form north of Sabie. The dolomite is fine-grained crystalline, grey to light grey in colour and often recrystallized to irregular white patches. Beds of black carbonaceous mudstone and shale occur and mechanical sedimentary structures are present. The formation decreases in thickness from 300 m in the north, until it disappears near Sudwala.

1.2.3.5 Frisco Formation

The Frisco Formation is characterized by the heterogeneity of its constituent lithologies. Dolomite, limestone, banded iron formation and to a lesser degree chert, are present in the unit. Sedimentary structures are rare. The formation is absent in the south.

1.2.4 THE PRETORIA GROUP

The Pretoria Group consists predominantly of shale and quartzite together with a volcanic unit and minor conglomerate, chemical and volcanic members. The Pretoria Group forms the high mountain ranges in the west of the area.

1.2.4.1 Rooihoogte Formation

Formerly known as the "Giant Chert" (Visser and Verwoerd, 1960) and the "Fountains Member" (Button, 1973a), the Rooihoogte Formation consists of a conglomerate-breccia at the base and quartzite above. The conglomerate is distinguished as the Bevet's Conglomerate Member. It is a residual sharpstone conglomerate composed of ill-sorted, angular fragments of chert (some reaching boulder-size) in a fine-grained matrix of sandy material. The Rooihoogte Formation rests unconformably on the Chuniespoort Group. Where it rests on one of the chert-poor formations, its thickness is less than 8 metres, but on chert- rich formations it can reach 56 m. It disappears north of Pilgrim's Rest.

1.2.4.2 Timeball Hill Formation

The Timeball Hill Formation comprises a shale zone up to 1600 m thick. Two bands of quartzite, the Klapperkop Quartzite Member, run through the middle of the zone.

The shale and mudstones are carbonaceous, thinly bedded, highly jointed, fissile and dark in colour (Fig. 1.13) They weather to light colours.

Flagstone occurs in the lower part of the zone in places. Siltstone beds are commonly developed. In the Sabie area there are anomalous dips due to slumping into solution cavities in the dolomite beneath, and further tilting of the strata sometimes occurs in the vicinity of diabase dykes.

The Klapperkop Quartzite bands (Figs. 1.14, 1.15) occur horizontally in the shale to give rise to broken cliff faces. The lower band averages 10 m in thickness. The upper band reaches 60 m in thickness in the north. Both bands have lower gradational contacts and abrupt upper contacts. The quartzite is medium to fine-grained. Ferruginous varieties weather to "snuff-box" structures ("Bushman paint pots").

1.2.4.3 Boshoek Formation

The Boshoek Formation forms a small, prominent cliff above the Timeball Hill Shale. It consists mostly of quartzite, conglomerate, shale and pyroclastics (Fig. 1.15).

1.2.4.4 Hekpoort Andesite

Flows of basaltic andesite are the most prominent rock type. Hekpoort Andesite reaches a thickness of 200 m.

1.2.5 TRANSVAAL DIABASE

Post-Transvaal diabase instrusions in the form of dykes and interbedded sills criss-cross the entire area. They are rare in the Wolkberg Group, but most common in the Pretoria Group, particularly in the form of sills (Fig. 1.16). Other basic rocks also make up these sills, those in the upper Chuniespoort Group and Pretoria Group being composed of pyroxenetic material. Sills occur most frequently between the two bands of Klapperkop quartzite and within the Boshoek Formation. Dykes run mostly in a N.N.E. direction in the Pretoria Group. In the Granite they run in all directions but are concentrated in a closely spaced series of east-west parallel lines east of Sabie.

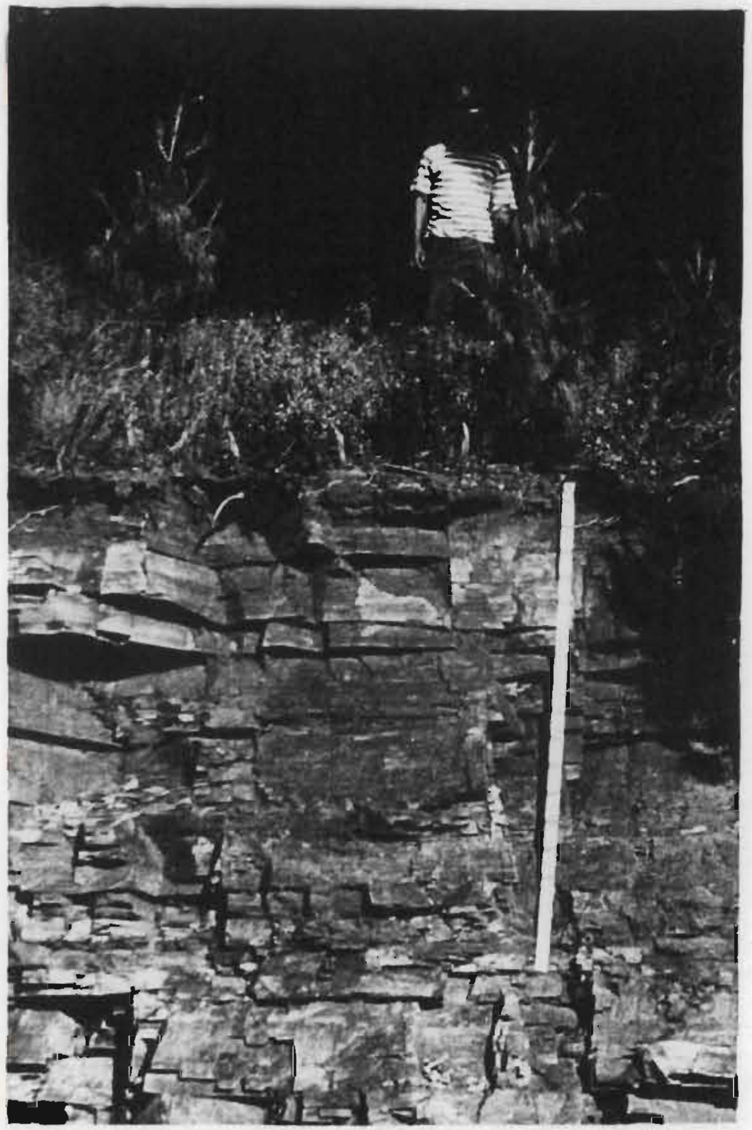


Figure 1.13 Timeball Hill shale (Ceylon S.F.).

Figure 1.14 Waterfall on Ceylon S.F. Formed by resistant Lower Klapperkop qtzt. Timeball Hill shale below

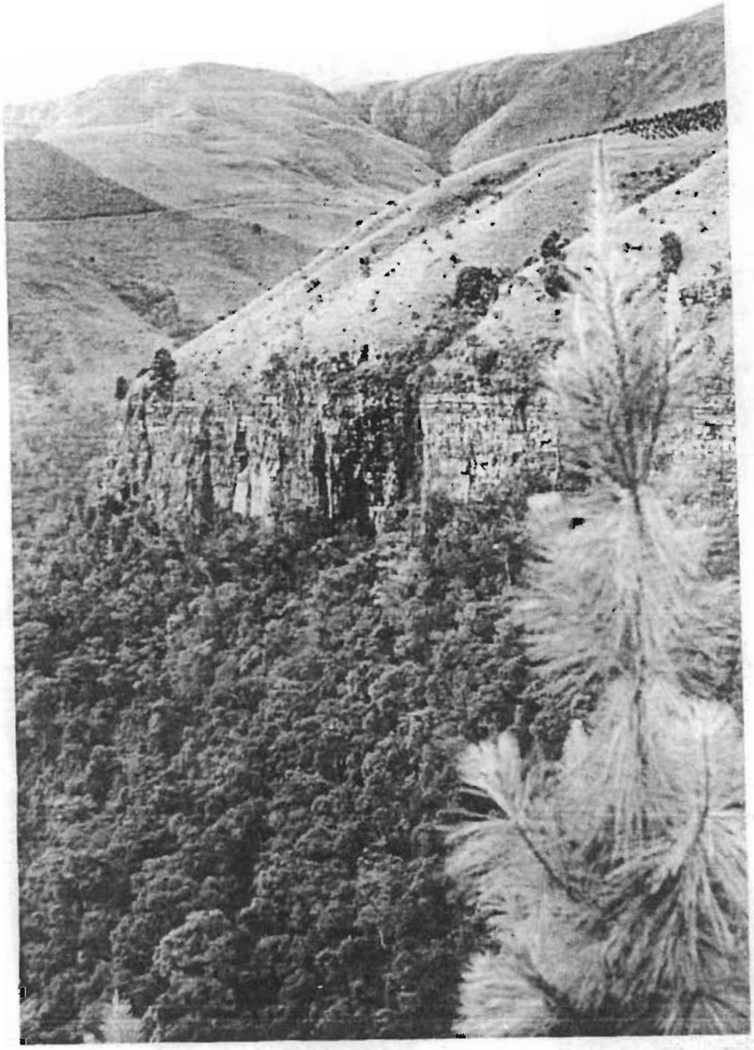


Figure 1.15 Upper Klapperkop qtzt, with Boshoek Fm in upper background (Long Tom S.F.).

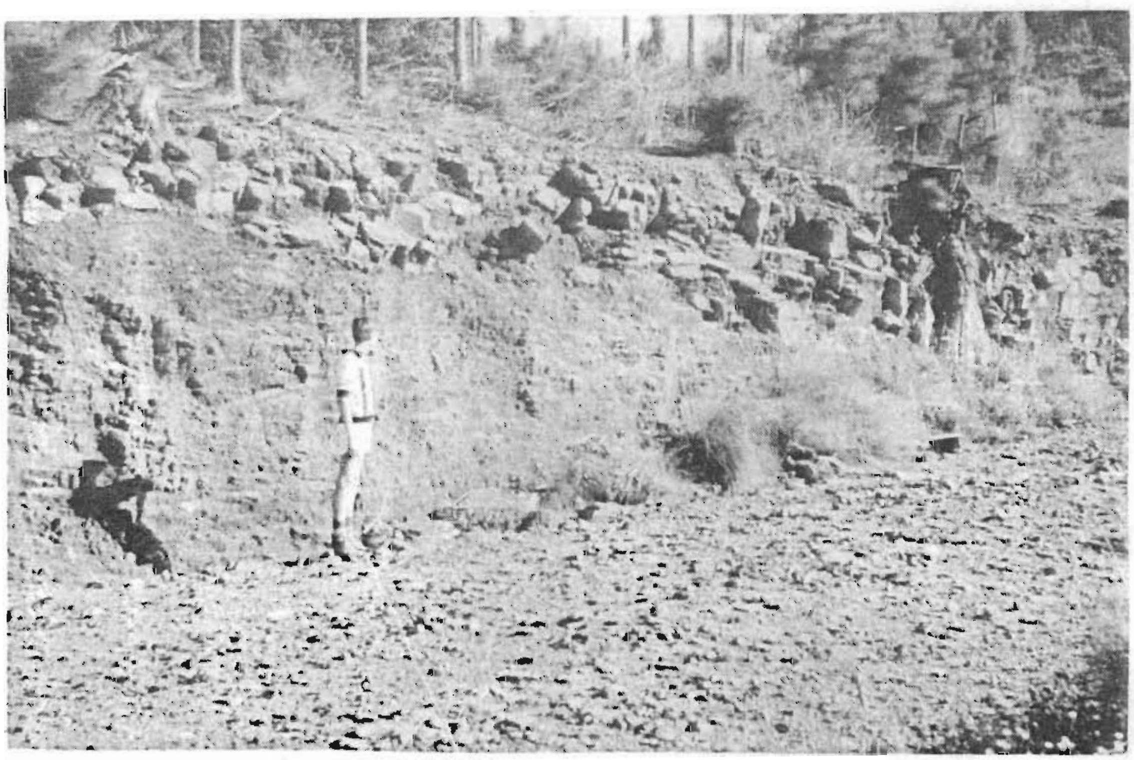


Figure 1.16 Weathered diabase sill overlain by Timeball Hill shale (Ceylon S.F.).

1.2.6 FAULTS

There is a close association between dykes and faults. The major faults trend in the same direction as the prominent dykes, which occupy many fault zones. The most consistent single linear structure is the one along which the Nestor Dyke is developed. It stretches from south of Sabie to beyond the Treur River (Bourke's Luck), with maximum displacement near Lisbon Falls.

1.2.7 ALLUVIUM

Deposits of alluvium and river terrace gravel are prominent in several places but particularly in the Sabie River valley above Sabie.

1.3 GEOMORPHOLOGY

The Great Escarpment can be regarded as the single most important geomorphic feature of the subcontinent, separating the elevated interior from the coastal hinterland. It was formed during the break up of Gondwanaland through rift faulting in the late Jurassic/early Cretaceous, and resulted from the high absolute elevation of the southern African portion of Gondwanaland (Partridge and Maud, 1987).

According to these writers, the landscape cycle which resulted from the fragmentation of Gondwanaland is referred to as the African cycle, during which erosion proceeded simultaneously at different levels above and below the Great Escarpment. In the sub-Escarpment zone much of the African surface has undergone dissection following rejuvenation of local river systems; remnants of the original surface are now confined to small areas on the interfluves. The African erosion cycle was of long duration, from late Jurassic/early Cretaceous to the end of the early Miocene, resulting in deep weathering and kaolinization of the underlying rocks. The subsidence of the Bushveld Basin and the slight westward tilting of the African surface occurred at the end of the early Miocene.

Within the study area three landsurfaces are distinguished by Partridge and Maud (1987), viz. the African surface (dissected), the Great Escarpment, and the mountainous areas above the African surface. For the purposes of this study these geomorphic regions are termed (1) the sub-Escarpment zone, (2) the Escarpment and (3) the western mountain ranges.

1.3.1 THE SUB-ESCARPMENT ZONE

Immediately below the Escarpment cliff line is a narrow belt of sharply dissected topography characterised by steep slopes and frequently exposed granite domes (Fig. 1.5), which may be termed the Upper Granite Region. It descends steeply to a Lower Granite Region of more gentle topography often expressed by convex ridges with a strong accordance of their summits. This is the larger region, upon which the majority of plantations on granite soils are located. These two regions were identified as major planation surfaces by Lageat and Robb (1984), but are not recognized as such by Partridge and Maud (1987).

1.3.2 THE ESCARPMENT ZONE

This prominent feature was developed primarily by the resistance of the Black Reef quartzite to erosion. The edge of the Escarpment varies in altitude from 1000 m near Rosehaugh in the south to nearly 2000 m at Mariepskop in the north. The deep gorges, along which the edge of the Escarpment is shifted westwards and downwards (due to the westerly dip), were formed along lines of weakness caused by faulting or dykes, e.g. the Sabie and Mac Mac Rivers. The altitude of the Escarpment edge can thus vary greatly over relatively short distances, e.g. a 600 m difference between Bakenkop (Spitskop State Forest) and Sabie Falls, within 11 km. The thickness of the cliff forming the Escarpment varies from a few metres in the south where it consists of Black Reef quartzite only, to hundreds of metres in the north where the Black Reef is not only thicker but is also underlain by quartzite cliffs of other formations as well. The Black Reef Formation forms the brow of several well-known waterfalls such as the Sabie Falls, Mac Mac Falls, Forest Falls and Berlin Falls. Lisbon Falls is formed by the Selati Formation. Prominent view sites such as The Pinnacle and God's Window are formed by the Black Reef Formation.

The Black Reef quartzite characteristically weathers to an exposed rock pavement on the surface of its westerly dip-slope, with "pillar and passage" topography caused by accelerated weathering along joints (Fig. 1.10). A maze-like accumulation of rock pillars with weird weathering forms ("gendarmes") is often formed, sometimes interspersed with deep crevasses (Fig. 1.17).

North of Sabie an easily recognizable boundary between the Wolkberg and Chuniespoort Groups is often formed by rivers and streams flowing in a southerly or northerly direction, e.g. Mac Mac and Treur Rivers. In contrast with the fairly flat dip-slope of the Wolkberg Group, the dolomite country is quite hilly and extends to the base of the high mountain ranges.

Dolomite rock is not often exposed within the high rainfall zone due to the solubility of the limestone. Exceptions are Spitzkop and the cliff line of the Eccles Formation (Figs. 1.18, 1.19), more resistant to weathering because of the high chert content. The solubility of the limestone has resulted in the formation of caves and sinkholes, usually more common within the Eccles Formation.

Figure 1.17 Black Reef qtzt "gendarme" near God's Window.

A characteristic of the upper hills of the dolomite country is that they are often capped or strewn with grey or light-coloured rocks. These rocks are remnants of the highly resistant Rooihoogte Formation and may often be found far from the nearest outcrop (Fig. 1.20). The Rooihoogte Formation separates the Chuniespoort Group from the Pretoria Group. It is sometimes exposed as a cliff line from Ceylon State Forest southwards. It forms the brow of waterfalls such as Bridal Veil and Lone Creek Falls as well as those on Brooklands State Forest.

1.3.3 THE WESTERN MOUNTAIN RANGES

The shales and quartzites of the Pretoria Group form high mountain ranges west of the Great Escarpment, decreasing in altitude northwards. A prominent peak in the south is Makobolwana (2222 m), with Mt Anderson further north being the highest in the range (2284 m). North of Mt Anderson the range is split by the Blyde River Valley. The western range has its highest point at Black Hill

Figure 1.18 Cave in the Eccles Fm (Ceylon S.F.).

Figure 1.19 Eccles Fm cliff line below Stanley Bush Kop (Mac Mac S.F.).

Figure 1.20 Talus slope with boulders from the Rooihoogte Fm (Brooklands S.F.).

(2079 m) on Morgenzon State Forest, ending near Bourke's Luck. The eastern range has its highest point at Mauchsberg (2115 m) between In-de-Diepte and Mac Mac State Forest, ending at Driekop. The western mountain ranges decrease in altitude northwards.

The resistance of the upper Klapperkop quartzite to weathering has resulted in the formation of high altitude plateaux at various locations along the range, e.g. at Lissabon State Forest, Hartebeesvlakte, and the summits of Black Hill and Mauchsberg. Numerous waterfalls are also formed by the two Klapperkop quartzite bands (Fig. 1.14).

1.3.4 DRAINAGE

The main drainage systems are the Nelsrivier to the south east, the Sabie and Mac Mac Rivers to the east and the Blyde and Treur Rivers to the north. The Nelsrivier is the largest of four rivers which run approximately parallel and drain into the Crocodile River, viz. the Houtbosloop, the Stadsrivier and the Sandrivier. The Nelsrivier drains a large area between Rhenosterhoek and Spitskop. The Sabie River has its source in the Mt Anderson range and flows E.N.E. to the lowveld. The Mac Mac River drains the dolomite country southwards from Driekop near Graskop until it swings abruptly east at Mac Mac

Falls and then continues its course to the lowveld. Numerous smaller rivers flow due east from the Escarpment north of Graskop. The Blyde River has its source in the mountains between Mt Anderson and Mauchsberg, flowing northwards at a fairly steep gradient to Pilgrim's Rest. It flows more slowly as far as Bourke's Luck from where it drops sharply into the well-known Blyde Canyon. It is joined at Bourke's Luck by the Treur River which drains the Black Reef dip slope in the northern part of the area.

In general, drainage lines are very closely related to linear structural features. The Blyde River for example, follows a course that is very close to the direction of a prominent fault-system known as the Frazer and Morgan Faults. The Klein Sabie, the Mac Mac and the Treur Rivers follow courses that are very closely related to the Nestor Fault. Furthermore, in numerous instances gullies follow structural lines such as faults, joints and dykes (the diabase dykes weather more readily than the sedimentary rocks) (Zietsman, 1964).

Of interest is the number of streams which flow in three different directions. They rise along the edge of the Escarpment, flow west down the dipslope, switching 90° north or south as they strike the formations of the Chuniespoort Group, then again 90° east to emerge from the Escarpment plateau on their course to the lowveld.

1.4 CLIMATE

1.4.1 PRECIPITATION

1.4.1.1 Rainfall

The Escarpment region falls within the summer rainfall area where most of the rainfall occurs between November and March. During this period rain is precipitated mainly in the form of thunderstorms and instability showers caused by convection in, and convergence of, tropical air masses (Weather Bureau, 1965). Light orographic rainfall associated with advection is also prevalent in the summer months, especially on the windward sides of the mountains and the Escarpment slopes. The small proportion of winter rainfall is derived mostly from orographic precipitation (Weather Bureau, 1965).

On average, the Escarpment area experiences a maximum of over 140 days per annum with measurable rainfall, including 60 to 80 thunderstorms which usually occur early in the rainy season (Weather Bureau, 1965). Prolonged periods of rain, usually in the form of drizzle, are common. Periods with seven consecutive days on which rain occurs can be expected twice per year on average, while periods with four consecutive rainy days may be encountered on as many as ten occasions per year (Weather Bureau, 1965).

Rainfall is generally reliable. In 58 years of recording, 78% of the annual falls lie within about 20% of the normal rainfall. A further 10% of annual falls may be regarded as "wet" years (120 - 140% of normal), and the remaining 12% as "dry" years (60 - 80% of normal) (Weather Bureau, 1965). Forest hydrologists at D.R. de Wet Forestry Research Centre (F.R.C.) recently analysed rainfall trends in the area by calculating a five-year running mean between 1921 and 1984 (Fig. 1.21). Distinct periods of rainfall above and below average, lasting approximately nine years each, are apparent (Dye and Coetser, 1986).

The regional climate is of the monsoon type in which three seasons can be recognized (Deall, 1985):

1. The rainy season of summer and late summer (November to March)
2. The cool dry season of autumn to early spring (April to August)
3. The warm dry season of spring and early summer (September to October)

The strongly seasonal nature of the rainfall at Tweefontein State Forest, which is typical of the area, is shown in Fig. 1.22.

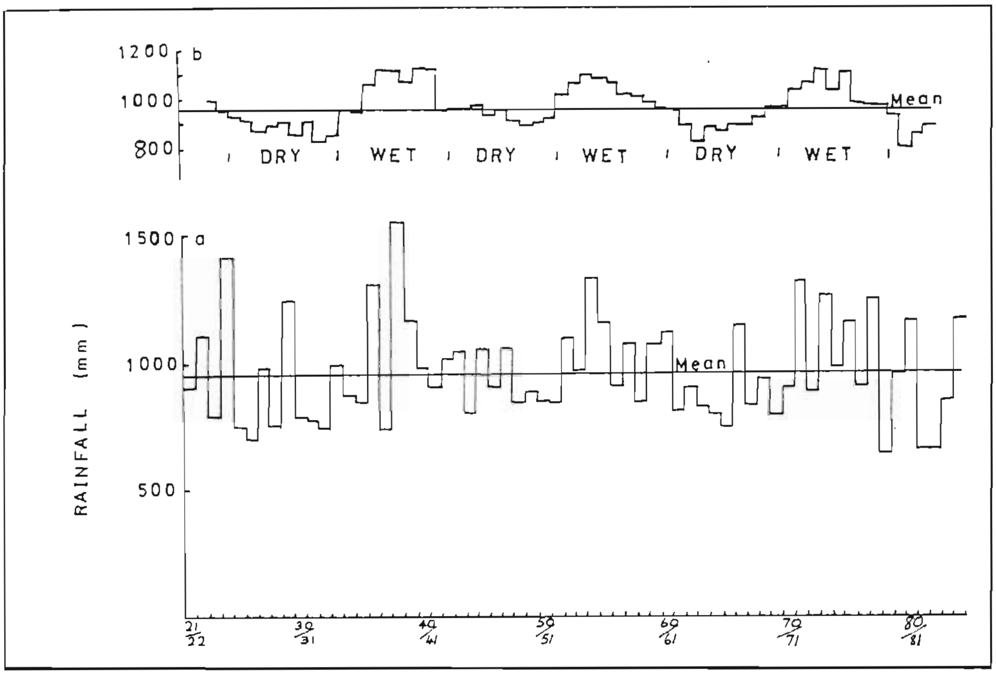


Figure 1.21 Annual rainfall totals (a) and a five-year running mean (b) for stations in the Escarpment area (Dye and Coetser, 1986)

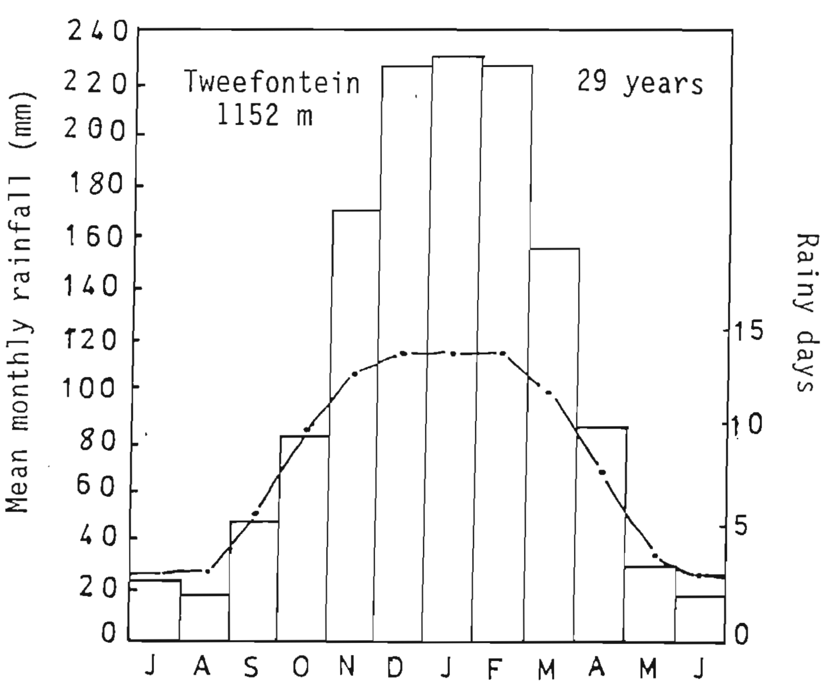


Figure 1.22 Annual march of mean monthly rainfall (histogram) and mean rainy days per month (graph) for Tweefontein S.F. (Deall, 1985).

Due to the broken topography there is considerable variation in the mean annual rainfall within the study area (Table 1.3).

Table 1.3 Mean annual rainfall (from highest to lowest) for 24 stations in the Escarpment area (compiled from plantation records and Weather Bureau data)

Station	Rainfall (mm)	Period (yrs)	Altitude (m)
Kowynspas	2027	6	1445
Long Tom	1853	17	1525
Mac Mac	1636	45	1250
Mariti	1594	29	1115
Lisbon	1563	25	1370
Hebron	1563	25	850
Blyde	1477	44	1400
Frankfort	1459	20	1050
Mariepskop	1379	43	1330
Spitskop	1371	45	1463
Bergvliet	1320	40	981
Wilgeboom	1297	50	1032
Hartebeesvlakte	1271	5	1920
Tweefontein	1258	75	1152
Ceylon	1248	44	1075
Salique	1225	40	850
Witklip	1203	40	1080
D.R. de Wet FRC	1220	26	950
Brooklands	1201	43	1234
Witwater	1139	57	1036
Swartfontein	1131	30	1152
Rosehaugh	1085	45	1112
Uitsoek	1030	10	1158
Morgenzon	881	29	1615

Unusually high rainfall was recorded at Blyde (2646 mm in 1978), Mariepskop (2623 mm in 1939) and Mariti (2318 mm in 1976). Unusually low rainfall was recorded at Morgenzon (384 mm in 1962), Witwater (617 mm in 1943) and Swartfontein (758 mm in 1965).

Mean annual rainfall is highest along the Drakensberg Escarpment, increasing northwards to a maximum in the Graskop area. It is also high on the eastern slopes of the high mountains west of Sabie, but decreases northwards along these mountains ranges. Local rain shadow areas are caused by the broken topography, but the rainfall decrease does not usually have serious implications for forestry. East of the lower granite region of the sub-Escarpment zone, however, the rainfall rapidly drops below the minimum required for forestry. There is a similar sudden decrease west of the summit of the western high mountain ranges.

Effective rainfall is strongly influenced by altitude (temperature). Thus the low mean annual rainfall figure of 881 mm at Morgenzon is sufficient for tree growth as evapo-transpiration losses are low (altitude 1615 m). On the other hand, the rainfall of 1225 mm at Salique (850 m) is barely sufficient for good tree growth.

1.4.1.2 **Other forms of precipitation**

Mist is common in summer, usually above an altitude of 1100 m. It plays an important role by reducing evapotranspiration. Substantial contribution to soil moisture from fog drip (condensation of mist on the foliage of plants) has been widely reported (Deall, 1985), but the measurement of through-fall under a *P. patula* stand at a misty site on the edge of the Escarpment near Sabie has shown this contribution to be negligible (Dye, pers. comm.). Dew precipitation occurs under certain conditions, reducing the rate and duration of evapotranspiration (Deall, 1985). Hailstorms of varying severity can be expected throughout the area, but on average only during four or five spring thunderstorms annually (Weather Bureau, 1965). The number of hail days per annum increases with altitude (Olivier, 1988). Snowfalls are infrequent, occurring during early spring above 1600 m in altitude and usually during high rainfall cycles.

1.4.2 TEMPERATURE

Temperature data for the region are scant. However, available information shows a direct relationship between temperature and altitude, consistent both for monthly and annual means (Table 1.4). Frost is prevalent in the winter months throughout the area, but frost-free sites are more common at low altitude (Table 1.5). From the aforegoing, it is apparent that late spring may be a critical time for plant growth due to the prevalance of extremely high day temperatures in the absence of rain (Deall, 1985).

Table 1.4 Annual march of temperature maxima, minima and means for stations at different altitudes in the Escarpment area (compiled from Weather Bureau (1954) data).

rature ieter :)	Station	Altitude (m)	Period	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
	Bushbuckridge	853	1905-12	28,3	28,2	27,2	25,9	24,4	22,6	22,3	23,8	25,9	27,8	28,3	28,5	26,1
	Bergvliet	981	1934-50	26,6	25,8	25,1	24,0	22,6	21,3	20,7	22,6	24,4	25,8	25,7	26,4	24,3
IUM	Tweefontein	1152	1931-50	25,4	24,8	24,3	23,3	22,3	20,8	20,3	22,1	24,0	25,4	25,2	25,4	23,6
	Graskop	1478	1911-48	22,8	22,3	21,4	20,6	18,9	17,4	16,8	18,9	21,0	22,7	22,8	22,7	20,7
	Bushbuckridge	853	1905-12	17,7	17,6	16,4	14,4	11,7	9,3	8,9	10,1	12,3	14,4	15,7	17,3	13,8
	Bergvliet	981	1934-50	16,4	16,6	15,7	14,3	11,6	8,6	8,0	9,6	11,8	13,6	14,9	15,6	13,1
IUM	Tweefontein	1152	1931-50	14,8	14,9	13,7	11,1	7,3	4,8	4,7	6,4	9,4	11,7	13,1	14,1	10,5
	Graskop	1478	1911-48	13,6	13,1	12,4	10,1	6,8	4,7	4,2	5,6	8,1	10,3	11,3	12,3	9,4
	Bushbuckridge	853	1905-12	23,0	22,9	21,8	20,2	18,1	15,9	15,6	16,9	19,1	21,1	22,0	22,9	19,9
ILY	Bergvliet	981	1934-50	21,5	21,2	20,4	19,2	17,1	14,9	14,4	16,1	18,1	19,7	20,3	21,1	18,7
	Tweefontein	1152	1931-50	20,1	19,9	19,1	17,2	14,8	12,8	12,5	14,2	16,7	18,6	19,1	19,7	17,1
	Graskop	1478	1911-48	18,2	17,7	16,9	15,3	12,8	11,1	10,5	12,2	14,5	16,5	17,1	17,5	15,1

Table 1.5 Occurrence of frost (< 0°C in Stevenson screen) at two stations in the Escarpment area (Deall, 1985).

	Tweefontein (1152 m)	Bergvliet (983)
Earliest date	23 May	-
Latest date	8 Sept	-
Average first date	23 June	-
Average last date	24 July	-
Average duration	31 days	-
Period of observation	71 days	15 yrs
Percentage of frost years	59 %	0

1.4.3 INSOLATION

Data for stations occurring within the area are scant. The average annual duration of bright sunshine in the mistbelt area is less than 60% of the possible sunshine (Deall, 1985). Physiographic variability of insolation due to slope and aspect also occurs. Daily incoming radiant flux densities on sloping terrain as a function of slope, aspect, and season have been presented for cloudless days in South Africa for the latitudinal range 20°S to 35°S by Schulze (1975). The following general trends for the study area were deduced by Deall (1985):

In midsummer, steep slopes receive less radiation than gentle slopes, regardless of aspect. Steep slopes with a south-facing aspect receive less radiation than those with a north-facing aspect. Incoming radiation on gentle slopes, however, is apparently unaffected by aspect. At the equinoxes and in midwinter, north-facing aspects receive greater radiation on steep slopes than they do on gentle slopes. The converse applies to south-facing aspects. Finally, regardless of steepness, slopes experience decreasing radiation as they tend more towards south-facing aspects.

1.4.4 HUMIDITY

In a study on *Eucalyptus grandis* near Sabie, Dye (1989) found that hourly transpiration could be predicted from ambient humidity alone, with a high degree of accuracy (R^2 = 0,92). Humidity is thus the single most important factor controlling transpiration rates. Humidity levels in turn are correlated with precipitation, temperature and wind (Deall, 1985). The highest mean values for the area are recorded in February-March and the lowest in June-July, with large fluctations in July-August when the extremes may vary between 2% and 96% (Deall, 1985).

1.4.5 WIND

Deall (1985) describes the winds as being south-easterly to easterly to north-easterly predominating during summer. These winds blow from the Indian Ocean and are often associated with anticyclonic systems, but can also be associated with cyclonic systems. Their persistence is often the harbinger of the steady rain, drizzle and mist so typical of Escarpment weather in summer. Winds which blow from the southerly to south-westerly sectors during early summer, especially in the afternoon, are often associated with thunderstorms. During winter these same winds are associated with cold fronts which are sometimes attended by mist and drizzle.

Violent bergwind conditions may occasionally occur. These winds become heated by compression as they drop over the Escarpment from the highveld plateau and are known to cause considerable physical and economic damage (in the form of breakage, lodging and windthrow) to timber plantations. Furthermore, the occurrence of such winds in the dry months of early spring constitutes a particularly serious fire hazard.

1.4.6 CLIMATIC CLASSIFICATION

According to Poynton's (1971) Silvicultural Map of Southern Africa, which is based on a modification of Thornthwaite's classification, there are two moisture regions and two thermal regions within the study area (Table 1.6). The scale of Poynton's map does not permit any useful differentiation of the area, however. Moisture zone B- lies in the extreme east at low altitude while zone B+ covers the larger proportion of the area. Thermal zones 4 and 5 would be roughly separated by the Escarpment.

Table 1.6 Silvicultural zones for the study area based on Poynton's (1971) classification.

(i) Moisture Regions

Zone	Climatic type	Moisture index
B+	Humid	>40
B-	Humid	20-40

(ii) Thermal Regions

Zone	Climatic type	Frost	Mean monthly minimum temperature for the coldest month
4	Warmer-temperate (mesothermal)	Light	0° - 5°C
5	"	Moderate	-5° - 0°C

1.5 SOILS

A reconnaissance survey of the soils in the Escarpment area was undertaken by von Christen (1959, 1964), who studied 40 profiles in an attempt to gain insight into nutrient cycling and podzolisation processes under pine stands. The location of these sites is unknown. Subsequently a land type survey of the area was conducted by Schoeman *et al* (1980), but this was based on only 10 profiles within the study area.

As part of this study 439 soil pits covering the widest possible range in soil and site conditions in stands of the three pine species were dug and profiles described. Although soil pits were located in pine stands only, the survey can be regarded as a representative sample of the soils of the Escarpment area, possibly with the sole exception of shallow lithosols which remain unafforested. The general description of the soils given here is followed by a more detailed one for the major geological subdivisions of potential importance to the growth of forest trees.

1.5.1 GENERAL DESCRIPTION OF SOILS

The general description which follows is based on a study of the 439 profiles and observations made during the survey. Statistics for some selected soil properties of potential importance for tree growth are summarized in Table 1.7. These soil parameters and their methods of determination are described in Chapter 2, para. 2.3 and in Appendix 7.

Origin

In the steep, mountainous terrain of the Escarpment area, most surface soils are of colluvial origin. The base of the transported soil zone is frequently characterized by the presence of a stone layer. Soil properties are strongly influenced by parent material and geological substrate.

Depth

The degree of ferrallisation of the solum, as well as of the underlying saprolite, is comparable to that of intensely weathered soils in the humid tropics (Von Christen, 1964). Based on a maximum of 150 cm (the depth to which soil pits were dug), the mean solum depth for soils under trees is greater than one metre. However, many very deep soils occur. The saprolites are generally many times deeper than their overlying sola.

Table 1.7 Summary statistics for selected soil properties of 439 representative sites in the Eastern Transvaal Escarpment area.

Variable		Units	Mean	Range	Std.Dev	C.V. %
A hor.	*depth*	cm	24	5 - 100	15,0	63
B "	*"*	"	88	10 - 142	40,4	46
Solum	*"*	"	111	15 - 150	42,6	38
A 1 hor.	*clay*	$g\ 100\ g^{-1}$	37	2 - 70	13,0	35
	silt	"	17	2 - 43	8,4	49
	sand	"	46	14 - 93	18,0	39
	fine sand	"	21	5 - 62	10,0	49
	medium sand	"	12	0 - 49	8,7	75
	coarse sand	"	14	0 - 55	10,6	75
B 21 hor.	*clay*	"	40	0 - 71	12,9	32
	silt	"	18	2 - 55	9,1	51
	sand	"	42	11 - 95	16,8	40
B hor.	*stone content*	"	23	0 - 80	23,2	10
Surface bulk density		$kg\ m^{-3}$	800	330 - 1400	220	28
Subsurface bulk density		"	990	380 - 1690	240	24
A 1 hor.	*hue*	index	6,3	2,0 - 12,0	1,84	29
	value	"	3,0	2,5 - 5,0	0,36	12
	chroma	"	2,8	0 - 6,0	1,25	45
B 21 hor.	*hue*	"	5,2	2,0 - 10,0	1,94	37
	value	"	3,7	2,5 - 6,0	0,68	18
	chroma	"	5,2	0 - 8,0	1,58	30
A 1 hor.	*Organic C*	%	3,6	0,4 - 9,5	1,74	48
	pH (H_2O)		4,8	4,0 - 6,0	0,37	8
	exch. acidity	$cmol\ (+)\ kg^{-1}$	1,5	0,1 - 4,8	0,89	59
	P	$mg\ kg^{-1}$	5,5	1,0 - 32,0	3,39	62
	K	"	36	2 - 251	26,7	74
	Ca	"	85	1 - 1332	144,1	170
	Mg	"	25	1 - 256	31,3	125
	Al	$cmol\ (+)\ kg^{-1}$	0,86	0,01 - 5,55	0,962	112
B 21 hor. Exch. K + Ca + Mg kg^{-1} clay		index	1,0	0,1 - 20,2	1,73	173

Drainage

The soils are generally well to excessively drained. It is somewhat surprising how few hydromorphic soils occur in spite of the high rainfall. These are mostly confined to valley bottoms on granite. Seasonally wet soils do occur, but due to the steep topography and the dip of underlying rock strata (above the Escarpment), water moves rapidly through the profile without becoming stagnant.

Texture

Clay loams to sandy clay loams are usual, but the range in texture is very wide indeed, depending on the parent material. The content of sand may be as high as 93 g 100 g^{-1} while that of clay may reach 71 g 100 g^{-1}. Some surface soils are high in fine and medium sand content. Silt ranges from 2 to 55 g 100 g^{-1}. Kaolinite is the dominant clay mineral present (Von Christen, 1964). In steep terrain the soils can be very stony, resulting in reduced rooting space and waterholding capacity.

Stone layers

Colluvial stonelines are frequent, usually occurring in a continuous or broken horizontal band in profile between the A and B horizons (Fig. 1.23), but sometimes resting on saprolite, buried talus, or bedrock. These stone layers represent the most recent major geological unconformity in the soil profile. They may vary considerably in thickness and in the size and compaction of the constituent fragments. Lithology is determined by origin, but may sometimes be mixed.

The processes involved in the development of stone layers is not known. It is possible that stone layers of small particle size (gravel, grit) may be biogenic, being formed by the action of termites which have carried the finer particles of soil upwards to form their termitaries, leaving behind a concentration of gravels and other particles too large to carry. Such a layer of coarse particles, being highly permeable, acts as a basal drain to protect their termitaries from inundation during periods of heavy rain. Generations of termitaries erode to contribute to a surface horizon of biogenic topsoil (Brink, 1985).

Structure

Most soils are apedal and structureless. Where structure occurs it is weaker than moderate in grade. Very coarse peds, up to one metre long, may sometimes be observed, but as no cutans are present, these could be due to drying cracks. There are generally few cutans, but under favourable conditions faunal activity can be high ("vermic" horizons). A fine, granular or structured surface horizon 5 to 10 cm thick may occur on deep, fertile soils under mature pine stands (Fig. 1.24). Similar structure is not found under adjoining unafforested grassland. This improvement in structure could be due to mycorrhizal activity (Schutz, 1982).

Density and consistence

In general soils are friable, with a very low bulk density. The loose, crumb-structured surface soils described in the previous paragraph would undoubtedly have resulted in low bulk densities being recorded. However, the unusually low values in Table 1.7 may also be due to possible errors resulting from use of too small a bulk density cylinder (Ch. 2, para. 2.3.2). Although the values may therefore be suspect, they are nevertheless useful for comparative purposes as the error is likely to have been consistent.

The compaction hazard of some surface soils may be high. Experience has shown that poorly-drained surface soils, with low biological activity and with a high fine and medium sand content tend to be susceptible to compaction when heavy logging equipment is used during wet climatic conditions (Grey, pers. comm.). In the study area the bulk densities of such soils may still be low, as the survey was carried out in first rotation stands not yet exploited.

Characteristic of Escarpment soils is the presence of a relatively compacted horizon just below the surface, particularly noticeable in the dry season. In the first example in Table 1.8 the dense horizon is the B 1; in the second case where the A horizon is thicker, it is lower down in the profile. The reason for the development of dense subsurface horizons is not clear. Soils on more gentle topography may well have been under extensive cultivation in the past, but dense horizons are also found on steep slopes which were unlikely to have been cultivated. There is a posibility of a relationship between this phenomenon and the exceptionally low levels of exchangeable calcium in the soils of the area (Schönau, pers. comm.), but this was not confirmed. Below the dense horizon there is frequently a decrease in density with increasing depth (Table 1.8). Some C horizons have been found to be extremely loose.

Colour

Soils are usually red, but range in hue from 10R to 2,5Y. Topsoils can be dark (value 2,5). Subsoils are never lighter than a value of 6. There are colour classification problems in the case of B horizons tinted from mauve to black by high soil manganese levels (Döhne, 1984).

Figure 1.23 Quartz stone layer in granite soil (Rosehaugh S.F.).

Figure 1.24 Loose, crumb-structured surface horizon under a mature pine stand (Tweefontein S.F.).

Table 1.8 Bulk densities for different horizons of two soils in the Escarpment area

Plot no.	Form	Horizon	Limits (cm)	Bulk density (kg m^{-3})
T55	Hutton	A 1	0 - 15	796
		B 1	15 - 40	1 036
		B 21	40 - 55	888
T17	Inanda	A 11	0 - 5	711
		A 12	5 - 25	795
		A 13	25 - 45	993
		A 3	45 - 60	1 029
		B 21	60 - 80	968
		B 22	80 - 110	977
		B 23	110 -(150)	973

Fertility

The organic carbon content of the topsoil ranges from very low to almost 10%, in which case it is an important nutrient reservoir for tree growth. The soils are acid, the lowest pH (H_2O) being 4,0. Available P and exchangeable K, Ca and Mg are very low, but exceptions do occur. Ca is the most deficient base, reaching "dangerously" low levels (Von Christen, 1959).

The sum of the exchangeable bases K, Ca and Mg per kg clay, which can be taken as an approximation of the clay S-value (Na was not determined), is low, and almost all soils are dystrophic. The only mesotrophic soils encountered were those on river terraces in a few low rainfall sites (Salique, Welgevonden). Some of the soils of the study area may be sensitive to the effects of air pollution at the deposition rates currently experienced (Tyson *et al*, 1988).

Classification

Soils were classified according to the South African binomial system (Mac Vicar *et al*, 1977). The dominant soil form by far is the Hutton (Table 1.9), with Farningham the dominant series. Profiles are so uniform, however, that location of the B 21 horizon is often very subjective. The presence of definite neocutanic B horizons in mountainous areas could not be ignored and these soils were classified as Oakleaf form. The frequency of duplex soils caused further problems in that a neocutanic horizon would sometimes overlie a lithocutanic horizon or even a red apedal horizon. In these cases the neocutanic horizons were regarded as diagnostic and the soils classified as Oakleaf form.

Table 1.9 Frequency table of soil forms in the Escarpment area

Form	Frequency %
Hutton	57
Oakleaf	13
Glenrosa	10
Griffin	7
Inanda	5
Clovelly	2
Mispah	2
Cartref	1
Kroonstad	1
Magwa	<1
Avalon	<1
Longlands	<1
Katspruit	<1
	100 % (n = 439)

Summary

The soils of the Escarpment area are mostly colluvial and of recent origin. They are usually deeply weathered, well-drained, red ferrallites. They have a very wide range in texture which is determined by the parent material. Duplex soils are frequent. Soils are often very stony, and colluvial stone layers are typical in many profiles. The soils are acid, dystrophic and of low fertility, but they posess good physical properties for tree growth. The dominant soil form is the Hutton.

1.5.2 SOIL PROPERTIES ACCORDING TO GEOLOGY

There are major differences in soil properties according to geological substrate. These differences are caused by the physical and chemical properties of the parent rock, its resistance to weathering, the slope of its dip and thus its influence on drainage, its altitude, and climatic influences prevailing at its particular location. As most geological boundaries are fairly easily discernible in the field, or have been mapped

(Fig. 1.3), soils were classified according to their geological substrate (para. 1.2). Rock types playing a minor role in soil formation were ignored, while those whose boundaries are not easily located or whose properties are very similar, were grouped. Six geological substrates were thus recognized, but the upper four formations of the Wolkberg Group were grouped into one class and designated *Dolomite* (Table 1.10). Diabase is briefly discussed as a seventh possibility.

The major properties of soils are listed according to geology in Table 1.10. The table should be interpreted bearing in mind that the values are means for the classes and that there is a wide range in properties within each class. Profile descriptions and analytical data for modal soils on each geological substrate are presented in Appendix 1.

1.5.2.1 Granite

Depth

Under the high temperature and rainfall conditions, granite rock weathers rapidly to form the deepest soils of the Escarpment area. Due to rapid vertical weathering, deep soils can be found even in ridge top positions, where a solum depth of seven metres was recently recorded. Saprolite is usually well-decomposed to great depths due to the long duration of the erosion of the African surface (para. 1.3). Narrow ridge crests and some very steep mid-slopes have been subject to erosion, resulting in shallower soils. In some areas the A horizon appears to have been eroded almost completely off the surface, sometimes exposing the underlying stone layer typically found in granite-derived soil. Some deep dongas are found, but it is not known how recently this erosion occurred. Certainly there is little evidence of donga erosicn under current land use.

Drainage

Granite-derived soils are well-drained to excessively-drained. Surface soils in particular tend to have a very low water-holding capacity. This is due to the high content of coarse sand and the strong cementation of clay particles into water-stable micro-aggregrates, resulting in a larger pore space. In combination with the non-expanding properties of kaolinite this results in rapid drainage and low plasticity. In spite of the generally good drainage of subsoils, hydromorphic soils tend to develop in bottomland positions and in

Table 1.10 Selected soil property mean values according to geology, for 439 representative sites in the Escarpment area

Variable	Units	Granite	Selati	Black Reef	Oaktree	Dolomite	Timeball
A hor. depth	cm	30	24	45	20	20	18
B " "	"	100	52	66	88	102	69
Solum "	"	129	74	104	109	122	87
A 1 hor.sand	g 100 g^{-1}	58	57	78	43	33	36
fine sand	"	16	27	29	26	19	22
medium sand	"	17	15	30	11	6	6
coarse sand	"	25	15	19	6	8	8
B 21 hor. clay	"	39	29	9	42	45	43
silt	"	11	17	9	17	26	21
clay + silt	"	50	46	18	60	70	63
B hor. stone content	"	14	29	10	11	17	47
Surface bulk density	kg m^{-3}	1010	630	870	680	720	660
Subsurface bulk density	"	1180	820	1130	950	890	860
A 1 hor. hue	index	6,1 (5YR)	7,6 (7,5YR)	8,1 (7,5YR)	7,2 (6,25YR)	5,9 (5YR)	6,2 (5YR)
value	"	3,0	2,7	2,6	2,9	3,0	3,1
chroma	"	2,8	1,4	1,1	2,3	3,3	3,2
B 21 hor. hue	"	4,3 (2,5YR)	6,7 (6,25YR)	7,2 (6,25YR)	6,9 (6,25YR)	5,1 (3,75YR)	5,3 (3,75YR)
value	"	3,8	3,8	3,8	3,9	3,4	3,6
chroma	"	6,1	4,4	4,1	4,9	4,8	5,1
A 1 hor.Organic C	%	2,3	5,3	3,5	5,2	3,5	4,3
pH (H_2O)		4,9	4,5	4,8	4,6	5,0	4,6
exch. acidity	cmol (+) kg^{-1}	1,2	2,2	1,3	1,4	1,0	2,2
P	mg kg^{-1}	6,7	6,3	6,2	3,4	3,9	6,0
K	"	38	34	18	25	46	32
Ca	"	117	43	13	16	132	39
Mg	"	34	12	6	9	37	15
Al	cmol (+) kg^{-1}	0,58	1,37	0,66	0,93	0,43	1,58
B 21 hor.Exch. K + Ca + Mg kg^{-1} clay	index	1,5	0,7	1,6	0,3	0,9	0,7
Number of sites		139	27	20	35	111	107

river terrace areas. These soils can be extremely wet during summer. This is in marked contrast to the soils of the other geological classes in similar topographic positions.

Texture

The average granite-derived surface soil is a sandy clay-loam with a coarse sand grading. In fact, surface soils on granite have by far the highest content of coarse sand of soils from all parent materials. B horizons are typically sandy clays with low silt.

Quartz stonelines are common, varying in thickness between 5 and 20 cm. They may be continuous over large areas or discontinuous, parallel with the surface in the lower part of the A horizon, or of irregular thickness at various depths and angles. The latter are probably *in situ* quartz remnants from the quartz-felspar veins within the granite which has subsequently completely weathered. The angular quartz fragments may be loose or slightly indurated. Concentrated quartz gritlines are also commonly found in upper B horizons. The general stone content of B horizons is low compared to that of other geological substrates.

Density

Bearing in mind the analysis problems described in para. 1.5.1, bulk density of both the surface and subsurface horizons is higher than that of soils of any of the other geological classes. Yet the compaction hazard is probably low due to the high coarse sand content and excessive drainage of the surface horizons (para. 1.5.1). Exceptions do, however, occur such as at Swartfontein where the fine sand content is high.

Shallow lithocutanic soils are common in the lower parts of Bergvliet and Rietfontein. They have developed over deeply weathered saprolite which has a dense packing and tends to set extremely hard when dry. These soils are thus poorer than they appear to be at first sight.

Colour

Some pockets of dark, organic-rich or humic topsoils occur in narrow drainage lines or concave footslopes; otherwise topsoils are light in colour. Soils of no other geological substrate have redder subsoil than that of granite, with the possible exception of diabase. Saprolite may be red to almost white in colour.

Fertility

On average, the organic carbon content of granite-derived surface soils is far lower than than on any other geological substrate. Exchange acidity is low, while pH is almost as high as that for dolomite-derived soils.

A horizon available P is higher than that on any other geological substrate while exchangeable K, Ca and Mg levels are only slightly lower than those of dolomite, which has the highest. Granite-derived soils are thus relatively fertile in the Escarpment area.

Classification

The dominant soil form is the Hutton, with hydromorphic soils in bottomlands and river terraces (Table 1.11). Series of the Hutton form were Hutton (26%) Farningham (72%), and Balmoral (2%).

Table 1.11 Frequency table of soil forms on granite parent material

Form	Frequency %
Hutton	70
Oakleaf	17
Inanda	5
Glenrosa	4
Clovelly	1
Cartref	1
Kroonstad	1
Katspruit	1

	100% (n = 139)

Summary

Granite-derived soils are the deepest in the Escarpment area. They are red, apedal and well-drained, with coarse sandy surface horizons and sandy clay loam to sandy clay subsoils. The compaction hazard is likely to be low. Although they are generally not very stony soils, quartz stone layers are common. For the Escarpment area the soils are relatively fertile. The Hutton form, Farningham series, predominates.

1.5.2.2 Selati

Soils on the Selati Formation are not extensive, occurring in a narrow band north of Sabie along the edge of the Escarpment where the Black Reef Formation has eroded away, and at Mariepskop. Parent materials are shale and quartzite. Soils derived from Selati quartzite only, are not easily distinguishable from sand derived from the Black Reef Formation, and reference to the geology map may sometimes be necessary.

Depth
Due to the irregular topography and rock outcrops along the edge of the Escarpment, Selati-derived soils are very variable in depth, but less so at Mariepskop where they are generally deep. Solum depth is the shallowest of all soils in the area.

Drainage
Due to the very high rainfall along the edge of the Escarpment, these soils are wet in summer, but dry in winter, due to their shallow depth to bedrock. The westerly dip of the underlying bedrock ensures good lateral drainage except where there is localized impedance due to the "damming" effect of rock outcrops, resulting in the accumulation of stagnant water. The generally sandy texture of the soils ensures the rapid movement of flush water through the profile. There is a tendency toward the formation of E horizons.

Texture
Selati-derived soils are usually sandy clay-loams with a coarse sand grade in the A horizon. Texture is determined by the parent material. Quartzite-derived soils are sandier than shale-derived soils, but parent materials are often mixed. Shale-derived B horizons high in clay are invariably overlain by sandy A horizons. These soils can be quite stony, and stonelines are common when the parent material is shale.

Density
The bulk density of both the surface and sub-surface horizons is low, and is in fact the lowest of all soils. Nevertheless the presence of a relatively high percentage of fine sand in the A horizon could result in a moderately high compaction hazard.

Colour
Surface soils have low values and chromas due to their high organic matter content. Subsoils are yellow, particularly with shale parent material.

Fertility

In contrast with soils on granite, Selati-derived soils contain a higher percentage of organic carbon in the surface horizon than that of any other geological substrate. This is due to the high rainfall and altitude of the Escarpment edge. The surface soils are the most acid of all soils, with pH the lowest and exchange acidity the highest.

Available P levels are relatively high for the area, as is exchangeable K. Ca and Mg are low, and Al is very high. The sum of available K, Ca and Mg per kg clay in the B 21 horizon is low. Soils derived from shale parent material are slightly more fertile than those from quartzite.

Classification

On the shallow soils along the Escarpment edge the dominant soil form is the Glenrosa. Although the organic carbon content of most surface soils is well over 2%, A horizons can rarely be classified as humic due to their shallow depth. West of the Escarpment edge, however, the soils become deeper and the Hutton, Oakleaf and Griffin forms are more common (Table 1.12).

Table 1.12 Frequency table of soil forms on Selati parent materials

Form	Frequency %
Glenrosa	38
Hutton	28
Oakleaf	18
Griffin	7
Inanda	3
Cartref	3
Mispah	3
	------
	100 % (n = 27)

Summary

Soils on Selati substrate are derived from shale and quartzite parent materials, which are often mixed. They are shallow and wet in summer but with good lateral drainage due to the sloping underlying bedrock and the generally sandy texture. Sandy clay loams predominate. The soils have a high stone content. Surface horizons are very dark in colour, with the highest percentage of organic carbon of all soils in the study area. They have the lowest density, but compaction hazard may be high in wet weather. Acidity is the highest of all soils. Fertility is moderate, but lower in the case of quartzite parent material. The Glenrosa form predominates. Selati-derived soils are not easily distinguishable from those of the Black Reef Formation.

1.5.2.3 Black Reef

Soils on the Black Reef Formation extend further south than those of the Selati Formation, but are also not extensive. South of Sabie all sandy soils along the edge of the Escarpment are derived from Black Reef parent material. North of Sabie they occur in a band parallel with Selati-derived soils, but generally further west down the dipslope.

Depth
As in the case of Selati-derived soils, soils on Black Reef substrate are very variable in depth due to the irregular outcrops of rock. They are mostly very shallow over solid bedrock, but plantations have been established where the soils are deeper, sometimes as isolated islands in the grassveld. Of all soils those derived from Black Reef have the deepest A horizons.

Drainage
The same remarks apply as in the case of Selati-derived soils, except that soils on Black Reef substrate tend to be wetter. This is due to their geomorphic position further down the dipslope where they receive a larger volume of flush water accumulated from the upslope watershed. Vertical drainage is frequently impeded by the blocking of fissures in the bedrock by ferricrete.

Texture
Soils are sandy loams, with the highest mean sand content of all soils (78 g 100 g^{-1}). A horizons have a coarse sand grade, but are the highest of all soils in medium sand. They are also the lowest in coarse fragment content.

Density
Bulk density is fairly high in comparison with Selati-derived soils. Soils on Black Reef also have the highest content of fine and medium sand and as such may have a high potential compaction hazard.

Colour

Of all soils, surface soils derived from Black Reef are the darkest in colour, with the lowest values and chromas. Hues of both the A and B horizons are the yellowest. B horizon chromas are also the lowest.

Fertility

Although the average organic carbon content of the surface soils is not the highest, organic, peaty topsoils are common, reaching a maximum organic carbon content of 9,3%. Acidity is not as high as in Selati-derived soils.

Available P levels are relatively high for the area, but topsoil exchangeable K, Ca and Mg are by far the lowest. Al is average. The sum of K, Ca and Mg per kg clay in the B 21 horizon is the highest, but because of the low clay content (9 g 100 g^{-1}), fertility is low.

Classification

The dominant soil form is the Hutton (Table 1.13), but a wide variety of forms occurs. No organic O horizons were found on the sites investigated under plantations, but it is probable that they do occur. Houwhoek and La Motte forms have been found in grassveld outside the plantations, this probably being the first report of podzols in the Transvaal (Fig. 1.25). Two soil forms occur for which there is no provision at series level in the S.A. binomial soil classification system, viz. Inanda and Magwa. Clay contents of the B 21 horizons are commonly 5 g 100 g^{-1} and lower, yet the minimum clay content given in the classification system for series differentiation is 15 g 100 g^{-1}.

Summary

Black Reef-derived soils are of variable depth over solid bedrock, with deep A horizons. The sandy texture and sloping bedrock generally ensure good lateral drainage, but the soils are wetter than those of the Selati Formation due to geomorphic positioning. The soils are droughty in winter. Sandy loams predominate and they are the sandiest of all soils in the study area. There could be a high potential compaction hazard in wet weather. Surface soils are the darkest of all and organic carbon content can reach high levels. They are the most infertile of all soils in the area. The Hutton form predominates, but hydromorphic soils are common.

Table 1.13 Frequency table of soil forms on the Black Reef

Form	Frequency %
Hutton	30
Mispah	15
Clovelly	10
Inanda	10
Oakleaf	10
Magwa	5
Griffin	5
Avalon	5
Longlands	5
Glenrosa	5
	------
	100 % (n = 20)

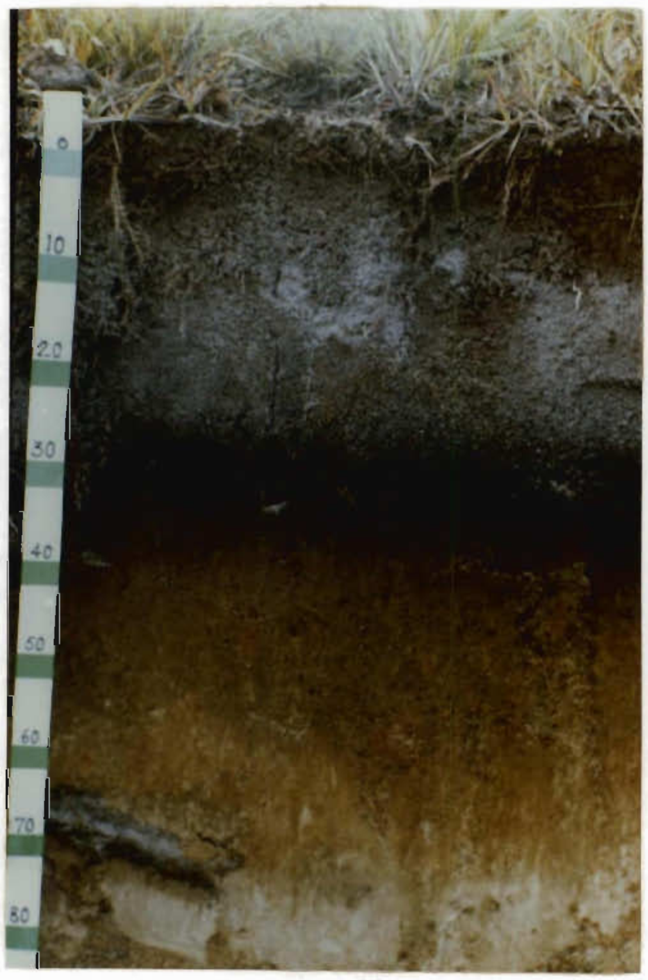


Figure 1.25 Houwhoek soil form in Black Reef sand (Blyde S.F.)

1.5.2.4 Oaktree

The Oaktree Formation is next in lithostratigraphic sequence to the Black Reef Formation. Being relatively thin (Table 1.2) and less resistant to weathering than Black Reef quartzite, soils derived from the Oaktree Formation are of patchy distribution on the westerly dipslope of the Escarpment. On this regional slope, colluviation has resulted in a mixed provenance of parent materials. Surface soils invariably originate from the sands of the Black Reef Formation, whereas subsoils high in clay content indicate Oaktree parentage. From the base of the dipslope to the upper boundary with the dolomite formations, however, soils of the Oaktree Formation may be recognized by the predominance of the Griffin form.

Depth
Oaktree-derived soils tend to be shallow on Black Reef bedrock in the east, but are moderately deep west of the dipslope. A horizons are shallow.

Drainage
Oaktree-derived soils can be very wet in summer and sometimes even in the dry season on the more moderate slopes, as indicated by the presence of the Griffin form. Where the Hutton form occurs, it is unusually wet. Thick litter layers are invariably to be found on these sites and during summers in high rainfall cycles the surface water in the litter layer creates marsh-like conditions under the pines. The rarity of mottles or rusty root holes indicates that there is nevertheless rapid movement of flush water through the soil. This was evident in freshly dug soil pits. Tree roots, however, are often severely restricted to the surface soil. The red apedal soils of the steeper slopes are much drier.

Texture
Surface soils of the Oaktree Formation have the highest content of fine sand (along with Timeball Hill), and the highest content of fine sand plus medium sand. They are generally clay-loams, except on some sites in the east where B horizons are overlain with a colluvial, dark sandy A horizon derived from Black Reef. Subsoils are high in clay and are classified as clays. Stone content is low.

Structure
Weak structure often occurs in the upper part of the profile. Some of the wetter B 21 horizons tend towards a massive condition.

Density

Bulk densities are low in the first rotation, but the high percentage of fine and medium sand in the surface horizon could make these soils the most susceptible of all soils in the Escarpment area to compaction, especially as surface soils remain moist for longer periods than any of the other geological substrates, and biological activity is low.

Colour

Surface horizons of Black Reef origin are usually dark, but even light coloured A horizons may have organic carbon contents of more than 2%. Yellow-brown apedal subsoils over red apedal horizons abound. The colour value of the B horizon is the highest of all soils. Tongueing between yellow and red horizons sometimes occurs.

Fertility

Organic carbon content is high. Acidity is average for the area. Surface soils have the lowest of all available P levels. Exchangeable K is low, but Ca and Mg are very low. The sum of exchangeable K, Ca and Mg per kg clay in the B 21 horizon is by far the lowest of all soils in the area. Oaktree soils are thus very infertile.

Classification

The dominant soil form is the Griffin (Table 1.14). The Hutton form is more common on the better drained sites, mostly of the Farningham series. The presence of structure, which is rarely strongly developed in the upper part of the profile, creates some ambiguity in classification.

Table 1.14 Frequency table of soil forms on the Oaktree Formation

Form	Frequency %
Griffin	49
Hutton	36
Clovelly	6
Oakleaf	6
Glenrosa	3
	------
	100 % (n = 35)

Summary

Oaktree-derived soils can be very wet in summer and differ from those of both Selati and Black Reef in that they can remain wet throughout the year. Surface soils are clay loams with a high fine sand content. The compaction hazard is likely to be the highest of all soils in the Escarpment area. Subsoils are high in clay and low in stone content. Weak structure is sometimes present in the upper horizons. Organic carbon content is high, but the soils are very infertile. The Griffin form predominates.

1.5.2.5 Dolomite

Dolomite-derived soils are almost as deep as those on granite. Only on ridge tops and steep slopes does the unweathered rock come close to the surface. Solution and removal of dolomite by ground and surface waters result in the formation of many caverns and underground channels, which often collapse. The normally horizontal overlying strata are often crumpled into irregular folds as a result. These folds may be seen quite close to the surface. They contain thin bands of soft chert, chalcedony and greyish blue shales, forming the C horizon in many profiles. True soil depth is difficult to determine in such cases (Fig. 1.26).

Drainage

Soils are well-drained and appear to remain so even in bottomland positions and in river terrace areas. This is in contrast with soils on granite, where hydromorphic soils tend to develop in these positions. The Griffin form is generally the wettest soil to develop on dolomite.

Texture

Surface soils are classified as clays, with a coarse sand grade. Fine sand is high, but medium sand is the lowest in the area. Subsoils are classified as silty clays. Their clay content is the highest of all soils in the Escarpment area, reaching a maximum of 71 g 100 g^{-1}. The silt content is perhaps the major difference between dolomite-derived soils and other soils as it is the highest, reaching a maximum of 51 g 100 g^{-1}. The high manganese content of these soils causes problems in particle size analysis (Appendix 7.1). The stone content is generally low, but stone layers containing either manganese concretions or chert fragments do occur.

Density

Bulk densities are average for the area. The compaction hazard is not likely to be high, as surface soil drainage is generally good.

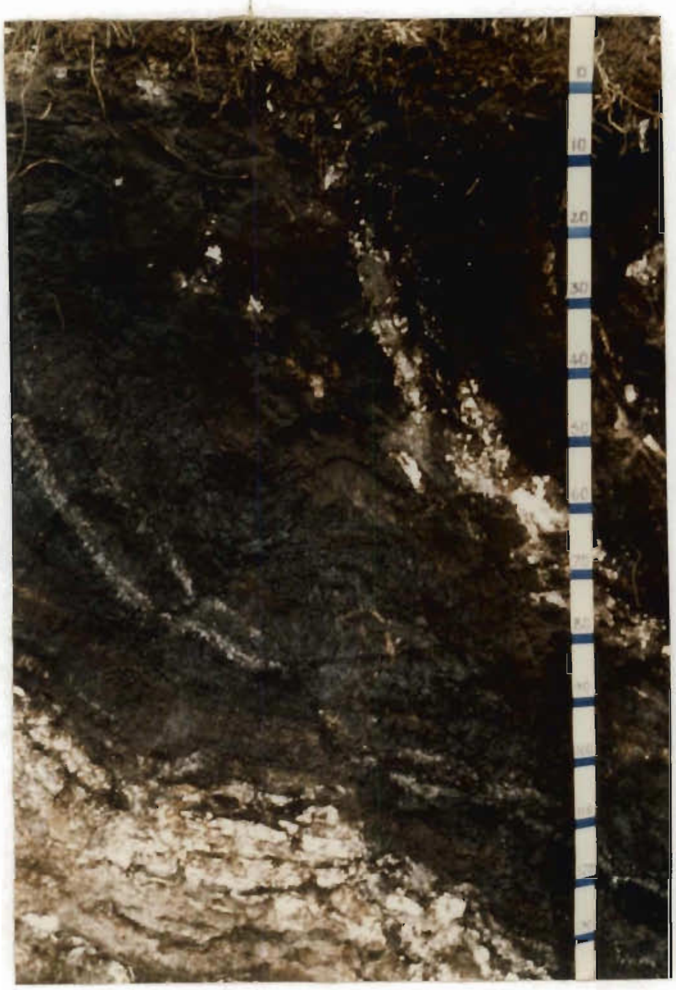


Figure 1.26 Collapse of strata due to solution and removal of underlying dolomite. Soil high in manganese content between folds of weathered chert (Brooklands S.F.).

Structure

Structure usually occurs only in the soils high in manganese (black manganese wad). It may vary from apedal to strong, usually angular blocky, and from fine to very coarse (Döhne, 1984).

Colour

Dolomite topsoils are the reddest of all soils in the area and also have the highest chromas. Subsoils are also very red, unless high levels of manganese are present in the soil. Colour classification of soils high in manganese presents special problems, as subsoils vary from dark red through mauve, purple, blue, to completely black. Standard soil colour charts make no provision for some of these colours (Fig. 1.26). Colour boundaries between soils high in manganese and adjacent red soils are very abrupt (Döhne, 1984). The black soils are of patchy distribution.

Chert rock frequently weathers to a loose, white powder, often visible in the profile as white spots in a red (or black) matrix. (Fig. 1.26). This is very characteristic of soils on dolomite.

Fertility

Of all soils in the Escarpment area, dolomite-derived soils have the highest pH and lowest exchange acidity, no doubt due to their limestone origin. Although available P levels are low, the exchangeable bases K, Ca and Mg are the highest in the area, while exchangeable aluminium is the lowest. It could be argued that the reason for this might be that dolomite (high bases) experiences a lower rainfall than Black Reef (low bases) which is at a higher altitude. However, correlation coefficients between rainfall and bases were low (K : -0,17; Ca : -0,28; Mg : -0,31). It thus appears more likely that the high levels of exchangeable bases on dolomite-derived soils can be ascribed to the parent material and high pH of these soils. Ca, for example, was reasonably well correlated with pH (r = 0,56). Manganese levels in the soils may reach toxic proportions for *P. patula* (Ch. 3, para. 3.3.2.4).

Classification

The Hutton form is dominant in dolomite-derived soils (Table 1.15). However, horizon delineation, designation and classification are often difficult where folding of the strata occurs near the surface and where black manganese wad occurs. In the latter case the recommended course of action would be to accept the classification as a black variant of the adjacent "normal" soil unless the structure indicates an Oakleaf form. Series of the Hutton form were Hutton (14%), Farningham (70%) and Balmoral (16%), thus very similar to soils on granite.

Table 1.15 Frequency table of soil forms on dolomite formations

Form	Frequency %
Hutton	73
Griffin	12
Oakleaf	9
Glenrosa	5
Clovelly	1

	100% (n = 111)

Summary

In many properties dolomite-derived soils resemble soils derived from granite. They are deep and well-drained. They have the highest clay content and are unusually high in silt. These soils are the most fertile of all soils in the area, with relatively low acidity. The dominant soil form is the Hutton, but black soils high in manganese occur which are hard to classify.

1.5.2.6 Timeball Hill

The soils of the Timeball Hill Formation are separated from the dolomite-derived soils by the occasionally prominent cliff line of the Rooihoogte Formation. Where the latter is not clearly visible, the boundary line cannot easily be determined on the surface. The Timeball Hill soils are recognizable by the high subsurface stone content.

Depth
Due to the steepness of the terrain and the resistance of the shale parent material to weathering, these soils are usually shallow. A horizons on Timeball Hill substrate are, in fact, the shallowest of all soils in the Escarpment area. There is surprisingly little accumulation of soil on lower slopes. Where there is no saprolite present, the underlying rock is usually sufficiently broken to allow a small degree of tree root penetration within the cracks.

Drainage
Soils are well-drained and hydromorphic soils are rare.

Texture
Timeball Hill-derived soils are clay-loams with a fine sand grade in the topsoil. The fine sand content is as high as that of soils on the Oaktree Formation. Subsoils are high in clay content, but can be quite sandy in limited areas below the two Klapperkop quartzite cliff lines.

These soils are by far the stoniest of all soils in the Escarpment area. Stones may be loose (Fig. 1.27), or compacted into stonelines, particularly where there is shale colluvium over diabase. Steep slopes and road banks can be unstable due to the amount of loose stones.

Density
Bulk density is relatively low and soils are not likely to be easily compacted.

Figure 1.27 Loose stone colluvium in Timeball Hill shale (Ceylon S.F.).

Colour

The soils are red, with the highest values and chromas in the topsoil of all geological substrates. Saprolite varies from red to white, sometimes in closely-spaced multicoloured bands, out of which the well-known "Sabie pottery" is cut.

Fertility

Topsoil pH is average for the area, but exchange acidity is as high as that of soils on the Selati Formation. Available P is relatively high, and exchangeable K is average, but Ca and Mg are low. Exchangeable Al is the highest of all soils in the area. The sum of exchangeable K, Ca and Mg per kg clay is low.

Classification

The Hutton form is the most common (Table 1.16). Series of the Hutton form were Wakefield (4%), Hutton (23%), Farningham (64%), Balmoral (9%).

Table 1.16 Frequency table of soil forms on the Timeball Hill Formation

Form	Frequency %
Hutton	49
Glenrosa	26
Oakleaf	19
Mispah	4
Clovelly	1
Griffin	1

	100% (n = 107)

Summary

The red soils of the Timeball Hill Formation are well-drained but shallow, and are the stoniest of all soils in the Escarpment area, with frequent stone layers. The soils are clay-loams of low fertility. The compaction hazard is probably not high. The Hutton form predominates.

1.5.2.7 Diabase

Diabase-derived soils are not easily recognizable as they are invariably buried below colluvial topsoil from the adjacent rock-type, from which they are mostly separated by a stone layer at 30 to 50 cm depth. Diabase soils therefore exist only as subsoils and their position as an important subdivision of soils relating to tree growth is questionable.

In the Timeball Hill Formation, diabase soils are recognizable by their very much deeper weathering than the adjacent shales. The spheroidal weathering of diabase rock is characteristic and is often a reliable indication of its presence even when the rock has completely weathered (Fig. 1.28). In granite and other substrates, soils from diabase intrusions are usually a darker red colour than the soils of the intruded rock-type. Diabase soils are high in silt, but low in coarse fragments. Structure is invariably present and neocutanic horizons are common.

Figure 1.28 Diabase saprolite (Ceylon S.F.).

1.6 VEGETATION

1.6.1 INDIGENOUS

The study area spans the two veld types of Acocks (1975), falling under his Inland Tropical Forest Types, viz. the North-eastern Mountain Sourveld (Veld Type 8) of the higher altitudes above the Escarpment, and the Lowveld Sour Bushveld (Veld Type 9) of the lower altitudes east of the Escarpment. Within the North-eastern Mountain Sourveld, Acocks (1975) recognizes three elements, namely a forest component, which he regards as the climax vegetation; a sourveld component, comprising replacement sour grassveld; and a scrubby thornveld component of the mountain slopes. Within the Lowveld Sour Bushveld, which is transitional between the Lowveld and the Northeastern Mountain Sourveld, he distinguishes between areas of "open parkland with tall well-spaced trees in tall grassveld" and "bushveld dotted with big trees".

A detailed vegetation survey of the area east of Sabie was recently undertaken by Deall (1985). He classified the vegetation into a number of forest, thicket, woodland, shrubland and grassland syntaxa by means of the Braun-Blanquet table method as well as by land types. He listed 848 species distributed among 436 genera and 120 families.

Indigenous forests are confined to fire-protected kloofs and southern aspects, but are not extensive in area. The largest are the Mariepskop Forest and the Maritzbos. Forests were exploited for timber during the gold mining era before exotic timber plantations were established, but virgin forest can still be found in inaccessible areas. A common species which, in a sense, typifies the forests below the Escarpment is *Anthocleista grandiflora* Gilg. One of the commonest species in forests above the Escarpment is *Celtis africana* Burm.f.

Grass species typical of the vegetation below the Escarpment are *Sporobolus* spp. and *Cymbopogon* spp., which occur mostly on disturbed sites, while *Loudetia* spp., *Themeda triandra* and *Panicum* spp. are common at higher altitude above the Escarpment (Dye, pers. comm.).

Aloe arborescens Mill is worthy of mention as it is invariably associated with quartzite rocks of the Black Reef Formation or the Klapperkop Quartzite Member of the Timeball Hill Formation. Similarly *Aloe dolomitica* Groenewald is frequently present among dolomite rocks.

Exotic timber plantations have created conditions favourable for the growth and spread of many indigenous plant species. Pioneer high forest species spread rapidly under mature stands of pine, particularly on the better dolomite and granite sites. Ground vegetation species do not offer much prospect as site indicators as they are so often suppressed by pine natural regeneration. In the absence of such suppression, however, the grass species *Oplismenus hirtellus* (L) Beauv. can be taken as a fairly reliable indicator of good site conditions. Continuous swards of this grass are a common sight under mature pines in lower and foot slope positions. The small but attractive orchid *Cynorkis kassneriana* Kraenzl. appears to thrive on the litter of *P. patula*.

Soil disturbance and the release of nitrogen from the mineralization of organic matter following clearfelling often result in the rapid invasion of the site by the indigenous grass species *Setaria megaphylla* (Steud.) Dur. & Schinz., one of the most serious weed species among newly planted pines and eucalypts. *Setaria* occurs mostly at lower altitudes but is spreading rapidly into the higher-lying areas. Another species which appears to be spreading and may eventually become a problem is the fern *Dicranopteris linearis* (Burm. f.) Underw. A pioneer woody species, *Acacia ataxacantha* DC., is frequently a problem below the Escarpment and on dry sites where it competes with plantation species for soil moisture.

1.6.2 EXOTIC

Commercial timber plantations are the major component of the exotic vegetation and were discussed in para. 1.1.2.

Several exotics have achieved prominence as weed species in commercial plantations, notably *Solanum mauritianum* Scop. (bugweed), *Lantana camara* L. (lantana), *Rubus* spp. (American bramble), *Caesalpinea decapetala* (Roth.) Alston (Mauritius thorn), *Phytolacca octandra* (inkberry) and various tree species such as eucalypts, wattle, blackwood, jacaranda and guava.

Weed species and competing vegetation, whether indigenous or exotic, are generally most serious at low altitude. Geological or soil parent material influence on the distribution of weeds is also apparent. Thus there are few problems with competing vegetation on soils derived from Black Reef quartzite or Timeball Hill shale.

1.7 SITE ANALYSIS

In order to determine whether any structure exists among the 439 sites (plots) or among the variables recorded at these sites, various multivariate analysis procedures were employed, using SAS (1985) programmes.

1.7.1 STRUCTURE AMONG SITES

An average linkage cluster analysis of the data was carried out. The tree diagram indicated that there is no grouping of sites with common properties other than in small clusters at a low hierarchical level. It may thus be concluded that the sites are evenly distributed with regard to the main sources of variation.

1.7.2 STRUCTURE AMONG SITE VARIABLES

Principal components analysis (PCA) and factor analysis were employed to determine whether any degree of structure was present among site variables, i.e. whether some variables were strongly correlated with others. Fifty-two variables regarded as being responsible for the major sources of variation among the 439 sites and also of potential importance for tree growth (Appendix 2) were chosen for analysis. The proportion of variation accounted for by the principal components with significant eigenvalues greater than 1,0 (the value generally recommended for biological data (Isebrands and Crow, 1975)) is shown in Table 1.17. PCA was based on the centred correlation matrix.

It is evident that relatively little structure is present, as there are 10 significant components accounting for 65,1% of the total variation, with the major component accounting for only 15,7% of the total variation. Variables associated with the first component (Appendix 2) were found to be *altitude*, *stoneline depth*, *weathering of subsoil*, *geology*, and soil acidity variables, indicating that the greatest source of variation is probably due to the escarpment gradient. The second component indicates that the largest proportion of the remaining variation could be due to the presence of sandy soils (sand positive, clay negative). The remaining components account for a relatively small percentage of the total variation. Factor analysis generally confirmed the findings of PCA that there is little indication of structure in the data.

Table 1.17 Principal components analysis of site variables

Principal component	Eigenvalue	Difference	Proportion of variation (%)	Cumulative variation (%)
1	8,18	2,35	15,7	15,7
2	5,83	1,80	11,2	26,9
3	4,03	0,50	7,7	34,7
4	3,53	0,29	6,8	41,5
5	3,23	0,86	6,2	47,7
6	2,37	0,19	4,6	52,2
7	2,18	0,59	4,2	56,4
8	1,59	0,11	3,1	59,5
9	1,48	0,02	2,9	62,3
10	1,45	-	2,8	65,1

CHAPTER 2

SITE-GROWTH RELATIONSHIPS

An understanding of site/growth relationships is essential for effective management of the forest resource. The following are some of the advantages which would follow from the identification of the key site factors influencing tree growth:

(i) Prediction of site index from quantitative site data.
(ii) A sound basis for the allocation of *P.patula* to the sites for which the species is most suited.
(iii) A basis for the monitoring of nutrient cycling for maintenance of site productivity.
(iv) A basis for nutrient diagnosis for improvement of site productivity, for example through fertilization.
(v) Site factors with minor roles would no longer have to be fruitlessly monitored.
(vi) Arising from the above, site classification for a variety of management and research purposes.

In this chapter the procedures used to identify the key site factors related to the growth of *P.patula* in the study area, and the results obtained, will be described. These methods also apply to the subsequent chapters in which relationships between site variables and other tree parameters are investigated.

It will be readily apparent, for example in the case of regression analysis, where the methods to be used depend upon the results of the previous step, that the usual headings of "Materials and methods" and "Results" would be inappropriate to describe the contents of this chapter. Instead the headings as used below are considered to be more logical.

2.1 REVIEW OF SITE-GROWTH RELATIONSHIPS

The growth of trees on a particular site represents an integrated response to a complex of many fluctuating and interacting environmental factors (Pritchett, 1979). The relationships between tree growth and site factors have been extensively reviewed by Carmean (1975), Coile (1952), Hägglund (1981), Jones (1969), Rennie (1963), Pritchett (1979), Ralston (1964) and others.

2.1.1 PHYSICAL SITE FACTORS

2.1.1.1 **Climate**

Temperature, radiation, evaporation, rainfall, drought, snow, hail and wind are examples of climatic variables found to influence tree growth in many site studies (Evans, 1978; Hägglund, 1981; Pritchett, 1979). Changes in macro-climatic conditions usually occur gradually over rather great distances and are best recorded by measurement of latitude (Graney and Ferguson, 1972) or longitude (Schönau, 1969). Paterson's "CVP-index" (Ralston, 1964) combined variables such as average temperature, precipitation and length of the growing season in an attempt to designate large-scale forestry zones. Effects may not be apparent at a local level until the growth gradient due to a limiting climatic variable becomes steep, as in mountainous areas where changes in altitudes cause great changes in temperature or precipitation over short distances (Pritchett, 1979). Non-availability of long-term meteorological records has imposed restrictions on most site evaluation studies (Grey, 1978).

2.1.1.2 **Physiographic factors**

Physiographic factors have generally been found to be of greater importance than climatic variables in the large number of site studies reviewed by Ralston (1964) and Carmean (1975), as they are more easily measurable than parameters such as temperature (altitude) and radiation (aspect) in smaller, local areas. Topography exerts an effect on growth through local modification of climatic and edaphic variables, particularly moisture, light and temperature regimes (Pritchett, 1979). Aspect appears to be of greater importance in temperate climates than in the sub-tropics (Grey, 1978). Physiographic factors such as slope, slope position, and various parameters expressing distance from the nearest ridge top, are indirect measurements of soil properties.

2.1.1.3 Soil properties

Within uniform climatic and physiographic regions, site differences in productivity can usually be separated on the basis of soil variables (Table 2.1). A great deal of research has been carried out in the USA, reviewed by Ralston (1964), Carmean (1975) and Pritchett (1979), who concluded that soil attributes expressing moisture, aeration and nutrients are the most important.

Table 2.1 Soil properties frequently related to site productivity from published North American reports (Pritchett, 1979) (Numbers in parentheses indicate number of reports to 1978)

Southern pines:	subsoil depth and consistency (22); surface soil depth (21); surface and internal drainage (18); depth to least permeable horizon (14); depth to mottling (13); subsoil imbibitional water value (8); N, P, or K content (6); surface organic content (22).
Northern conifers:	surface N,P, or K content (17); surface soil texture (14); drainage class (11); depth of surface soil (8); A1 organic content (7); thickness of B horizon (5); stone content (5).
Eastern oaks:	surface soil depth (14); depth of A + B (14); subsoil texture (9); exchangeable base content (7); soil pH (6); surface soil texture (5); organic or N content (4).
Eastern hardwoods:	depth to pan or mottling (20); surface soil texture (19); soil drainage (11); nutrient content (8); depth to water table (7); depth of A horizon (7); subsoil texture (3); organic content (3).
Western conifers:	effective soil depth (18); available moisture (6); surface soil texture (6); soil fertility (4); subsoil texture (3); stone content (3).

Parent Material

Parent material is a major contributor to the process of soil development, and as such it has an indirect effect on tree growth through its influence on soil chemical, physical and microbiological properties. This influence can, however, be modified by climate (Keenan and Candy, 1983; Mashimo and Arimitsu, 1981; Meeuwig and Cooper, 1981; Pritchett, 1979; Shrivastava and Ulrich, 1978).

Soil depth

Soil depth determines the volume of soil available to tree roots and thus nutrient and water supplies. The absolute and effective depths are, however, not necessarily the same, as a high water table, toxic substances, or an impervious layer may completely restrict root penetration in a soil that would otherwise permit deep rooting (Pritchett, 1979). Effective depth is not easy to define, as it is different for different species. It has proved to be an important variable in recent studies by Hunter and Gibson (1984), Ryan (1986), Turvey *et al* (1986) and Vincent (1986).

Soil water

Tree growth is controlled more by water availability than by any other factor on most sites (Pritchett, 1979). For a given overhead climate, soil water is primarily determined by soil depth, structure and texture. Growth improves with an increase in silt and clay content, as a result of more favourable moisture and nutrient supplies, to a point where further increases in the proportion of fine particles produces aeration difficulties (Ralston, 1964). Stone and gravel content can also modify water regimes. Soil water was an important variable in studies by Brown and Loewenstein (1978), Schlatter and Gerding (1984), Shoulders and Tiarks (1980), and White (1982a,b).

Soil aeration

Aeration effects on site productivity are difficult to separate from those of soil depth, texture and water. Lack of oxygen prevents root penetration and exploitation of nutrients (Pritchett, 1979). Aeration is reduced by poor drainage, high water tables, fine texture and high bulk density (Geyer *et al*, 1980; Hamilton and Krause, 1985; Hunter and Gibson, 1984; Keenan and Candy, 1983).

Soil nutrients

There was less emphasis on fertility factors in earlier studies due both to the frequent correlation between nutrient supplies and variables used to describe other soil properties, and to the difficulty in diagnosing nutrient status (Ralston, 1964; Hägglund, 1981). Soil chemical parameters found to be significant in many studies include N, P, K, Ca, Mg, micronutrients, organic matter, exchange acidity and cation exchange capacity (Grey, 1978). N deficiencies are more common in cool climates while P deficiencies are more frequent in exotic pine plantations in the southern hemisphere (Pritchett, 1979). Most studies have indicated the importance of the A horizon (Grey, 1978). Recent studies include those by Harding *et al* (1985), James *et al* (1978), Turvey *et al* (1986) and Vincent (1986).

Soil classification

Soil classification systems have seldom proved useful indicators of forest site productivity (Carmean, 1975; Cook, *et al* 1977; Graney and Ferguson, 1971; Grey, 1978; Ralston, 1964), but recent exceptions were found by Evans (1971), Mashimo and Arimitsu (1981) and others. Success would depend upon the nature and purpose for which the classification system was designed (usually agriculture) and the range of soils present within the area.

2.1.2 BIOLOGICAL FACTORS

There are several biological factors which are capable of influencing site productivity and are a potential source of error in site factor evaluation. They are often difficult to identify and quantify. The reviews of Pritchett (1979), Ralston (1964) and Shrivasta and Ulrich (1978) cover some of the more important factors.

Stand density can influence mean height, especially on poor sites. Genetics is of particular importance in afforestation with exotics, and seed sources, even if known, are difficult to quantify. The same applies to the role of competing vegetation in the early life of the stand and of pests and diseases. There are also the effects of industrial pollution (Hägglund, 1981) to consider.

2.1.3 METHODS OF RELATING SITE FACTORS AND TREE GROWTH

The primary aims of site assessment research are generally one or more of the following:

1. To identify the key factors of the environment which can be related to tree growth, thus for example providing a basis for site classification

and mapping, or for defining similar sites for use in monitoring site changes.

2. To forecast the potential tree growth of unafforested land, usually by means of a prediction equation or simulation model.

3. To forecast the potential tree growth of different species for a particular site, i.e. for species- site allocation.

Methods to achieve these aims can be grouped broadly into three site assessment approaches, viz. analogue methods, the holistic approach and the site factor evaluation technique.

Analogue methods are essentially broad, regional classifications within continents or countries, for example those based on climate (Rennie, 1963). They give poor predictability when applied to small areas as many of the location-specific parameters which influence production are not taken into consideration. Nevertheless analogue methods based on climate (temperature, rainfall, evaporation and moisture deficit) have been successful as a first step in the introduction of exotic tree species, for example the silvicultural zones of South Africa as designated by Poynton (1971). Cajander's classic study of the forest types of Finland is an example of the productivity classification of forest in relation to the ground vegetation (Rennie 1963). Certain characteristics of the natural vegetation have been used for classification of the indigenous forests of the Southern Cape (Laughton, 1937; Von Breitenbach, 1974).

Holistic approaches seek to classify the environment as a whole, and may also include socio-economic data. Some examples are reviewed by Carmean (1975) and Jones (1969), who conclude that the system requires much subjective judgment and intuition.

The most generally applicable method for relating site and tree growth is the site factor evaluation method, also termed the "factorial approach" (Jones, 1969), "soil-site evaluation" (Carmean, 1975) or "site factor analysis" (Grey, 1978). The method has been used on a large scale, particularly in the U.S.A. The technique is based on the measurement of an index of tree growth on a wide variety of sites, which is then related to environmental factors measured on the same sites by means of regression analysis or other multivariate procedures. The resulting model can then be used to predict tree growth. The steps required in applying the method are outlined below.

2.1.3.1 Sampling procedure

Whether a species should be studied over its entire natural or planted range, or within a smaller, localized area, depends on the objectives of the survey. Climatic factors can be treated as continuous variables where obvious variations exist, but subdividing large geographic areas into relatively homogeneous climatic provinces has proved to be a simpler way of resolving climatic differences (Grey, 1978; Pritchett, 1979). Even within smaller, uniform climatic areas, many workers have stratified their data according to geographical, altitudinal or soil parent material zones (Carmean, 1975; Graney, 1975; White 1982a). Well-defined geological, soil, topographic, climatic and vegetal boundaries are necessary (Carmean, 1975). With increasingly larger geographic areas there is a decreasing correspondence between site index and soil factors (Fralish and Loucks, 1975; Grey, 1983 a; Pritchett, 1979; Turvey *et al*, 1986).

Site plots should represent the full range of tree growth and site conditions occurring within the defined study area. Extremes must be adequately represented (Carmean, 1975). This should be the main consideration in deciding on the number of plots to be laid out. To obtain a reliable estimate of variance, the number of plots should also be much greater than the number of site variables to be investigated (Rayner, 1980). Grey (1983 a) suggested 1,5 times as many.

2.1.3.2 **Index of tree growth**

Earlier studies in natural stands used tree height as a dependent variable, adjusted by introducing age as an independent variable, but recently site index (determined from stem analysis and site index curves) has become the more commonly used parameter (Carmean, 1975). As mean height is more sensitive to stand density than top height, the latter is preferable (Hägglund, 1981). General Yield Class (a standardization of top height for age) has become popular in Britain (James *et al*, 1978; White, 1982a; Worrell, 1986). Other indices of tree growth used have been height growth intercept (to remove the effect of competing vegetation in the early life of the stand), volume, mean annual volume or biomass increment, basal area and others (Hägglund, 1981; Harding *et al* 1985; Mader, 1976). Parameters which are not based on some measure of height are, however, affected by stand density, and as such do not respond similarly to site factors (Mader, 1976).

2.1.3.3 Related site factors

Primary influences on growth, such as light intensity and duration, temperature and CO_2 concentration are difficult to measure adequately in the forest. In this type of survey it is necessary to resort to assessing some of the secondary factors of a site which have the important property of close correlation with the primary ones, for example aspect and altitude. A second difficulty is that it is impossible to measure every conceivable factor. The number must be restricted, with the penalty of possibly omitting a significant one (Evans, 1971). Selection of independent variables is based on the understanding of physical and biological processes underlying site productivity, on the findings of others (para. 2.1.1) and on practical considerations such as cost and ease of measurement. Awareness of the possible role of biotic factors (para. 2.1.2) is essential. Variables must be quantifiable, and special attention to interactions and necessary transformations is required (Carmean, 1975).

Recent developments in selection of suitable independent variables include the use of monoterpenes to express differences in genotype (White, 1982a), of tatter flags to measure exposure to wind (Worrell, 1986), new expressions of radiation indices (Tajchman and Lacey, 1986), and new terrain classifications (Grey, 1983 b).

2.1.3.4 Regression analysis

Modelling relationships between site index and site properties is fairly difficult (Hägglund, 1981). It is necessary to bear in mind that the independent variables in a model are not necessarily the cause of variation in the dependent variable, only that in terms of the data available, the independent variables are related to the observed changes in the dependent variable in a strictly statistical sense (Montgomery and Peck, 1982). The point is also made by Harding *et al* (1985) that interpretations of the biological meaning of parameters selected for a model are tenuous until the trends or relationships in question can be tested in controlled experiments.

Nethertheless multiple linear regression analysis based on the method of least squares is still the most important, widely used and studied form of regression analysis (Cox, 1984 b).

There have been many recent developments in multiple regression techniques and diagnostics, such as best subsets regression, recursive residuals (Galpin and Hawkins, 1984) and various methods of handling multicollinearity such as ridge regression. Several workers have used principal components analysis to select uncorrelated site variables (Vallée and Lowry, 1972; White, 1982 a,b), but the method is not necessarily superior to other selection methods (Hunter and Gibson, 1976; Graney, 1974; Hoerl *et al*, 1986; Page, 1976; White, 1982a,b). Factor analysis has also been used (James, *et al*, 1978). Discriminant analysis has sometimes been used instead of multiple regression analysis (Harding, *et al*, 1985; Turvey, *et al*, 1986; Vincent, 1986).

A coefficient of multiple determination (R^2) of 0,7 is usually considered a successful functional relationship (de Barros *et al*, 1976), but Mashimo and Arimitsu (1981) consider an R^2 less than 0,8 to be unsuccessful. In practice an R^2 between 0,6 and 0,8 is generally considered acceptable.

2.1.3.5 **Application**

The necessity for testing site models on independent data (validation) before being recommended for use is widely acknowledged (Carmean, 1975; Mc Quilkin, 1976). A commonly used method is to exclude a certain percentage of the plots from the regression analysis for use as an independent data set (cross- validation) (Graney, 1974; White, 1982a,b). It is important to bear in mind that a site model applies only to the particular area studied, and only to the particular site conditions sampled within the study area (Carmean, 1975). Extrapolation should not be done without testing. The quality of a model cannot be sufficiently judged until it has been in large scale practical use for some time. However, there is almost nothing written in the literature about feedback from practical application (Hägglund, 1981).

2.1.4 SITE FACTOR EVALUATION STUDIES IN P.PATULA

Although the general site requirements (mainly climatic) of *P.patula* are known (Esterhuyse, 1985; Poynton, 1979; Schönau and Fitzpatrick, 1981; Schönau and Schulze, 1984; Wormald, 1975), there have been relatively few site factor evaluation studies in this species, especially in comparison with other pines.

Mexico

Virgin stands in Oaxaca ranging in age between 65 and 133 years were surveyed by Castaños (1962), using 45 0,1 ha plots. 28 site factors were tested in regression analysis. Rainfall was excluded as it was a uniform 1700 mm anually throughout the area. A model containing three independent variables was found to explain 53% of the total variation in height growth. These were soil depth, altitude and aspect. The most important factor was soil depth, an increase in depth from 0,30 m to 1,25 m resulting in a 5 m increase in site index. *P.patula* is replaced by other species on shallow soils. A decrease in altitude from 3000 m to 2400 m improved site index by 3,5 m. Westerly aspects were better than easterly, presumably a temperature effect.

Malawi

Using 85 and 33 plots respectively for two different geographical areas, Hardcastle (1976) tested four site factors in regression analysis. Only aspect and topographic position were significant, aspect decreasing in importance with increasing rainfall. R^2 values obtained were 0,29 and 0,53 respectively. The dependent variable was top height at 15 years.

Swaziland

A site assessment of the Usutu Forest was undertaken by Evans (1971; 1974) to provide a basis on which a comparison of growth between two rotations would be feasible. The influence of 58 site factors was studied on 61 0,04 ha plots. A model with altitude, percentage distance from ridge top to valley bottom, soil classification, subsoil P and surface soil exchangeable K explained 84% of the variation in top height at 12 years. Altitude was curvilinear in its effect.

South Africa

In the Umzimkulu district of the Transkei, Grey (1978) used 120 variable-sized plots to study the influence of 47 site factors on tree growth. Three different measures of tree growth were tested as dependent variables, viz. site index at 20 years derived from the curves of Marsh, (1957) (1), site index derived from the curves of Crowe, (1967) (2), and mean annual volume increment at 20 years (MAI20 Index) (3). In the case of (1), the regression model contained the variables altitude, landsurface unit and slope % and had an R^2 of 0,48. Model (2) contained altitude, percentage distance from ridge crest, and parent material. R^2 was 0,46. Model (3) contained percentage distance from ridge crest, landsurface unit and slope %. R^2 was 0,42. No soil variables appeared in any of the models.

In the Natal Midlands, Schönau and Wilhelmij (1980) examined the relationship between 11 site factors and expressions of tree growth similar to those used by Grey (1978), described above, using 50 plots. Models were obtained which contained rainfall, soil form, clay content, bioclimate and age, but R^2 values were so low (0,21; 0,30) that they could not be used for prediction.

None of the *P.patula* models reviewed above were tested.

2.2 FIELD PROCEDURES

2.2.1. PLOT DISTRIBUTION

At the time the survey for this study was undertaken, the age class distribution was heavily-skewed in the direction of the older age classes, with few second rotation stands yet old enough for sampling. Sampling was thus confined largely to the older stands (mean age 38 years) with the following advantages:

(i) Selection of first rotation stands reduced the possibility of second rotation effects on soil properties and other uncertainties.
(ii) There was greater uniformity of seed source (para 2.3.3).
(iii) The stands had been subjected to roughly similar climatic influences.
(iv) *P.taeda* and *P.elliottii* stands available for later study of comparative site requirements were of similar age.
(v) As all thinnings had been completed many years previously, full occupancy of the site by the trees was ensured.
(vi) The survey was carried out soon after the appearance of new insect pests such as the black pine aphid. The index age of 20 years selected for the dependent variable and obtained by stem analysis of these older trees (para. 2.4) was therefore well before such pests could have had any influence on growth.
(vii) Selection of older stands meant that more information on tree growth could be obtained, e.g. top height at 30 years as a dependent variable (para. 2.4.3).

The statistical requirement that plots be located without bias was difficult to meet in view of the strict criteria for site selection (para. 2.2.2 below) as well as the availability of suitable stands. It was felt, however, that a relatively large number of plots would compensate for any bias. Consequently 159 plots were established, and distributed in such a manner as to cover the maximum possible range of (i) site conditions and (ii) tree growth. Plot distribution is shown in Fig. 2.1. Plantations not sampled were either too young at the time or comprised other species. In practice mostly State forests were sampled as stand history had been better recorded. Plot location by plantation is detailed in Appendix 3. Plots were numbered sequentially as measurement proceeded.

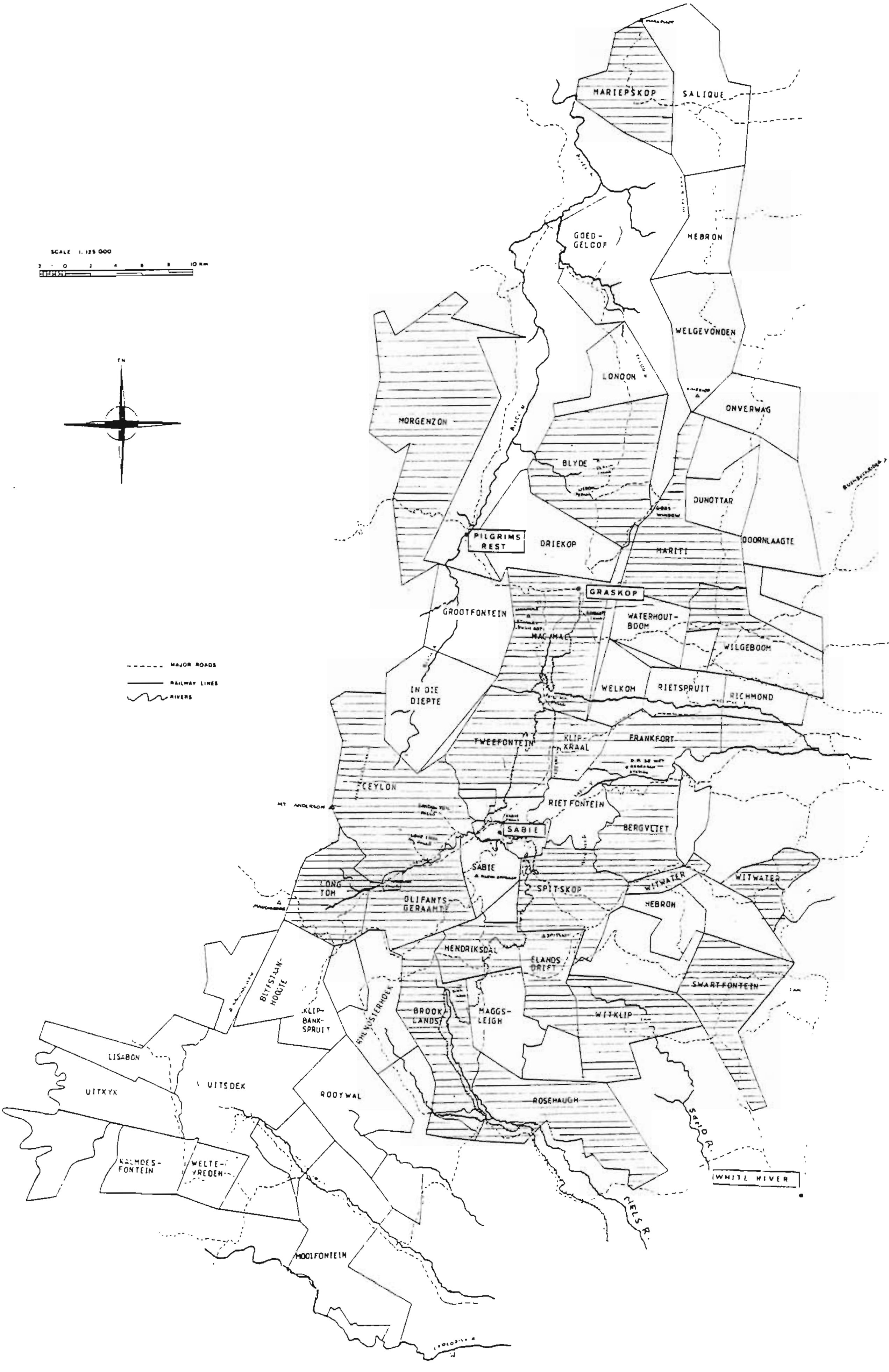


Figure 2.1 Plantations sampled (shaded) for *P. patula* site study.

2.2.2. PLOT ESTABLISHMENT

Strict criteria were employed in selecting sites for plot layout. Due to the generally low stocking of stands following final thinning, a plot size of 0,1 ha was used, circular in shape but with the dimensions corrected for slope where this was steep. Uniformity of site conditions and tree growth over an area of at least 0,15 ha was essential. No changes in slope, surface topography or aspect were permissible. Soil uniformity was checked by augering. Stands with uneven stocking, uneven tree sizes (presence of wolf trees), windfalls, breakages or other recent disturbance were not eligible. Compartment registers were consulted for evidence of previous problems such as at establishment, insect pests, diseases, fire, hail or storm damage. Short slopes with a change in site index within 0,15 ha were avoided. Plot boundaries were sited at least a tree length from compartment boundaries, gaps in the canopy and roadsides.

An L-shaped soil pit with sides 1,5 m long was dug to 1,5 m depth or rock in the centre of each plot with the outside angle of the L orientated to point upslope, and with one side 2 m from the nearest dominant tree (for comparable descriptions of rooting). All trees were numbered and D.B.H.'s measured overbark with a diameter tape to the nearest 0,1 cm. To obtain the correct height for measurement of breast height, a 1,3 m stake was driven through the litter to the mineral soil, always on the upper side of the tree when there was a slope. All other measurements and sampling are fully described later. Data were recorded on a field sheet, an example of which is shown in Appendix 4.

2.3 INDEPENDENT VARIABLES

Selection of independent variables was based both on studies reported in the literature involving similar species and conditions, and on personal observation. Special attention was given to factors which varied greatly within the study area, for example altitude and soil properties. There were nevertheless factors of potential importance which could not be included due to difficulty of measurement. One example was the percentage distance from ridge top to valley bottom, a factor which has proved of importance in several studies but which could not be assessed because dense undergrowth in the majority of stands would have made the cost prohibitive. Another example was the occurrence of mist, a meteorological variable difficult to measure. Surface stone was buried under forest litter and could also not be assessed.

The site factors (independent variables) selected for evaluation of their relationship with tree growth (dependent variable) in this study are listed in Table 2.2, together with their summary statistics (mean, range, standard deviation and coefficient of variation). It should be noted that a term used to describe a specific site factor will be printed in italics when it refers to a parameter or variable in statistical analysis. For example, clay may be used as a term to describe soil texture but *clay* is a variable in g $100g^{-1}$ used as a predictor in regression analysis. A full description of site parameters and their method of determination follows, under the headings of (1) field measurable factors, (2) soil analytical factors and (3) biological factors.

2.3.1 FIELD MEASURABLE FACTORS

These are parameters which could be recorded directly in the field (variables X_1 to X_{50} in Table 2.2), as opposed to parameters requiring collection of samples and laboratory analysis.

2.3.1.1 Geographic - climatic - topographic variables

X_1 *Latitude* (minutes)

Expressed as minutes south of 24^o for ease of computation, and obtained from 1:50 000 topo series maps (Government Printer, 1973-1980)

Table 2.2 Summary statistics for independent variables

No.	VARIABLE	UNITS	MEAN	RANGE	S.D.	CV %
FIELD	MEASURABLE FACTORS					
	GEOGRAPHIC-CLIMATIC-TOPOGRAPHIC					
X_1	Latitude	mins.	63,5	3,2 - 78,4	8,4	13
X_2	Longitude	"	49,0	40,5 - 60,0	5,0	10
X_3	Rainfall	mm	1417	695 - 2054	262	19
X_4	Altitude	m	1380	912 - 1984	241	17
X_5	Aspect	degr.	192	5 - 360	104	54
X_6	Slope	%	16,3	1 - 60	12,6	77
X_7	Aspect x slope	index				
X_8	Slope shape	"	1,57	1 - 3	0,67	42
X_9	Slope p. Chorley	code				
X_{10}	Slope p. Conacher	"				
X_{11}	Slope p. Local 1	"				
X_{12}	Slope p. Local 2	"				
X_{13}	Radiation index	index	0,98	0,72 - 1,08	0,06	6
X_{14}	R.I. summer	"	31,5	27,4 - 32,9	0,75	2
X_{15}	R.I. equinoxes	"	25,6	17,0 - 29,8	1,76	7
X_{16}	R.I. winter	"	15,7	5,8 - 20,8	2,48	16
X_{17}	R.I. sum	"	72,8	53,3 - 78,6	4,23	6
	SOIL DEPTH					
X_{18}	A 1	cm	19	6 - 50	8,6	46
X_{19}	A	"	24	6 - 80	13,4	57
X_{20}	B	"	87	10 - 142	40,4	46
X_{21}	Solum	"	111	26 - 150	42,2	38
X_{22}	Roots	"	77	8 - 150	47,2	61
X_{23}	Fine roots	"	123	26 - 150	39,7	32
X_{24}	≥ 10 % stones	"	51	1 - 150	52,9	103
X_{25}	≥ 20 % "	"	65	1 - 150	55,1	85
X_{26}	≥ 30 % "	"	73	1 - 150	56,1	77
X_{27}	≥ 40 % "	"	83	1 - 150	56,8	68
X_{28}	≥ 50 % "	"	92	10 - 150	91,7	61
X_{29}	≥ 60 % "	"	101	10 - 150	54,6	54
X_{30}	≥ 70 % "	"	111	10 - 150	50,9	46
X_{31}	≥ 80 % "	"	129	15 - 150	39,9	31
X_{32}	≥ 90 % "	"	137	26 - 150	30,4	22
X_{33}	100 % "	"	141	30 - 150	24,7	18
X_{34}	Highest clay horizon	"	55	10 - 150	33,0	61
X_{35}	Highest clay increase	"	43	5 - 150	33,5	78
X_{36}	Effective rooting depth	"	81	1 - 150	55,6	69
	OTHER SOIL MOPHOLOGY					
X_{37}	A 1 vol of stones	%	4,1	1 - 56	8,2	198
X_{38}	A " "	"	5,9	1 - 56	9,7	64
X_{39}	B " "	"	25,9	1 - 80	23,9	92

Table 2.2 (continued)

No.	VARIABLE	UNITS	MEAN	RANGE	S.D.	CV %
X_{40}	Solum vol of stones	%	20,6	1 - 67	18,5	90
X_{41}	Geology	code				
X_{42}	Weathering	index	2,3	1 - 3	0,7	29
X_{43}	Structure	code				
X_{44}	Permeability	index	3,4	2 - 4	0,7	20
X_{45}	A hue	code				
X_{46}	value	index	3,0	2,5 - 4,0	0,36	12
X_{47}	chroma	"	2,8	0 - 6,0	1,35	49
X_{48}	B hue	code				
X_{49}	value	index	3,7	2,5 - 6,0	0,67	18
X_{50}	chroma	"	5,3	1,0 - 8,0	1,64	31
SOIL ANALYTICAL FACTORS						
	TEXTURE					
X_{51}	A 1 clay	g 100 g^{-1}	39	5 - 66	12,7	33
X_{52}	silt	"	17	4 - 39	7,9	47
X_{53}	clay + silt	"	56	8 - 85	17,7	32
X_{54}	total sand	"	45	15 - 92	17,7	40
X_{55}	fine sand	"	21	6 - 58	10,3	48
X_{56}	medium sand	"	11	1 - 43	8,9	80
X_{57}	coarse sand	"	12	1 - 44	8,7	70
X_{58}	B 21 clay	"	39	0 - 68	13,1	33
X_{59}	silt	"	18	3 - 41	8,0	45
X_{60}	clay + silt	"	57	6 - 89	16,8	30
X_{61}	total sand	"	43	11 - 94	16,8	39
X_{62}	fine sand	"	20	4 - 63	10,4	52
X_{63}	medium sand	"	10	1 - 46	7,3	77
X_{64}	coarse sand	"	14	2 - 46	9,0	65
	BULK DENSITY					
X_{65}	Surface b.dens	kg m^{-3}	760	330 - 1400	230	30
X_{66}	Subsurface b. dens.	"	950	380 - 1600	250	27
X_{67}	B.dens. ratio		0,79	0 - 1	0,14	18
X_{68}	Depth highest b.dens.	cm	14	1 - 40	7,9	56
	CHEMICAL					
X_{69}	A 1 P	mg kg^{-1}	6	1 - 26	3,7	61
X_{70}	K	"	38	9 - 251	31,7	85
X_{71}	Ca	"	43	1 - 770	92,5	218
X_{72}	Mg	"	19	1 - 256	27,2	142
X_{73}	Al	cmol(+) kg^{-1}	0,91	0,02 - 3,96	0,93	103
X_{74}	B 21 P	mg kg^{-1}	3	1 - 26	3,5	121
X_{75}	K	"	17	1 - 151	18,4	106
X_{76}	Ca	"	21	1 - 547	49,9	241

Table 2.2 (continued)

No.	VARIABLE	UNITS	MEAN	RANGE	S.D.	CV %
X_{77}	Mg	mg kg^{-1}	9	1 - 97	14,1	155
X_{78}	Al	cmol(+) kg^{-1}	0,33	0,01 - 2,38	0,47	143
X_{79}	Bulk surface P	mg kg^{-1}	8	2 - 28	3,9	48
X_{80}	K	"	42	11 - 268	36	85
X_{81}	Ca	"	70	1 - 1050	180	258
X_{82}	Mg	"	27	3 - 283	49	179
X_{83}	Al	cmol(+) kg^{-1}	1,49	0,03 - 3,86	0,85	57
X_{84}	A 1 organic C	%	4,0	0,6 - 9,5	9,5	47
X_{85}	pH KCL		3,9	3,3 - 4,7	0,24	6
X_{86}	pH H_2O		5,2	4,4 - 6,2	0,29	6
X_{87}	exch. acidity	cmol(+) kg^{-1}	1,8	0,2 - 4,8	0,98	55
X_{88}	B 21 pH KCl		4,4	3,7 - 6,2	0,43	10
X_{89}	pH H_2O		5,2	4,4 - 6,2	0,29	6
X_{90}	exch. acidity	cmol(+) kg^{-1}	0,6	0,03 - 3,20	0,66	113
	EXCH. BASES (SUM)					
X_{91}	A 1 exch. bases (soil)	cmol(+) kg^{-1}	0,46	0,09 - 6,59	0,75	162
X_{92}	B 21 " " "	" "	0,22	0,02 - 3,39	0,37	167
X_{93}	A 1 " " (clay)	" "	1,29	0,16 - 11,85	1,83	142
X_{94}	B 21 " " "	" "	0,58	0 - 9,17	0,88	152
X_{95}	A 1 effective CEC	" "	2,25	0,44 - 6,78	1,00	44
X_{96}	B 21 " "	" "	0,81	0,07 - 3,65	0,74	92
X_{97}	A 1 base status	ratio	20	4 - 97	21,4	105
X_{98}	B 21 " "	"	34	4 - 94	24,3	72
X_{99}	A 1 Al saturation	%	38	1 - 156	31,7	84
X_{100}	B 21 " "	"	44	1 - 451	56,6	128
BIOLOGICAL FACTORS						
	STAND FACTORS					
X_{101}	Age		37,8	29 - 47	5,3	14
X_{102}	Stand density	N ha^{-1}	335	210 - 540	39,5	18
X_{103}	Stand density @ 20 yrs	N ha^{-1}	688	270 - 1499	144,4	32
X_{104}	Mean DBH	cm	41,3	33,5 - 57,6	4,1	10
X_{105}	Mean height	m	30,2	20,6 - 43,3	4,83	16
X_{106}	Mean tree vol.	m^3	2,65	1,07 - 7,81	1,10	42
X_{107}	Form factor	ratio	0,61	0,39 - 0,77	0,07	12
X_{108}	Bark thickness	cm	3,26	2,26 - 4,17	0,38	12
X_{109}	Total basal area	m^2 ha^{-1}	29,8	16,5 - 46,1	5,61	19
X_{110}	Mean " "	cm^2	1368	884 - 2606	269,5	20

X_2 *Longitude* (minutes)

Expressed as minutes east of 30^0 for ease of computation, and obtained as above.

X_3 *Rainfall* (mm)

Expressed as mean annual rainfall for the period of growth of the trees from 0 to 20 years for each plot. The data base was 24 rain guages within the area. The method of estimation of rainfall for each plot is described in Appendix 5.

X_4 *Altitude* (m)

Height above sea level was derived from the location of the plots on the 1:50 000 topo series maps (Government Printer, 1973-1980). These readings were checked in steep terrain by means of altimeters, corrected for hourly barometric pressure fluctuations monitored at the nearest forest station.

X_5 *Aspect* (degrees)

Aspect was measured in degrees from magnetic north using a prismatic compass held at right angles to the contour (parallel to the direction of slope). Correction for magnetic declination was not regarded as justified at this stage as the difference in variation between magnetic and true north over the study area was less than half a degree.

X_6 *Slope (%)*

This was measured with a percentage Abney level, sighting from the highest point of the plot boundary to the eye-level mark on a stake planted at the lowest point on the plot boundary.

X_7 *Aspect x slope interaction*

The combined effect of aspect and slope was assessed, using the method described by Stage (1976).

X_8 *Slope shape*

This was coded as 1 = convex, 2 = straight and 3 = concave, referring to the plot surface and its immediate environment.

X_9 *Slope position* (Chorley model)

For details of slope position models X_9 - X_{12} see Appendix 6.

X_{10} *Slope position* (Conacher & Dalrymple model)

X_{11} *Slope position* (Local model 1)

X_{12} *Slope position* (Local model 2)

X_{13} *Radiation index*
The ratio of interception on a slope to that on a horizontal plane, based on calculated radiation interception for the 15th of each month and expressed as a yearly average (W. Bond, pers. comm.).

X_{14} *Radiation index : summer*
Daily incoming radiation fluxes under cloudless conditions in summer calculated from nomographs supplied by R.E. Schulze (pers. comm.) and described in his publication on this subject (1975). Inputs are *slope*, *aspect* and *latitude*.

X_{15} *Radiation index : equinoxes*
As above, for equinoxes

X_{16} *Radiation index : winter*
As above, for winter

X_{17} *Radiation index : sum*
Sum of X_{14} to X_{16}.

2.3.1.2 Soil depth factors

These were recorded as a mean of 3 measurements at the extremities of the L-shaped soil pit, to a maximum depth of 150 cm, depending on the presence of rock.

X_{18} *A 1 horizon depth* (cm)
This corresponds with the depth sampled for chemical and physical analysis.

X_{19} *A horizon depth* (cm)

X_{20} *B horizon depth* (cm)

X_{21} *Solum depth* (cm)

X_{22} *Depth of roots* (cm)

The lowest depth reached by roots of medium to large diameter (visual estimate).

X_{23} *Depth of fine roots (cm)*

The lowest depth reached by fine roots (visual estimate of size) of frequency class 2. The concentration of roots was recorded on a visual scale of 0 to 6. Frequency 2 was selected, as frequency 1 roots are often found at maximum depth even in shallow soils of the Mispah and Glenrosa forms, bearing no obvious relationship with site index.

X_{24} *Depth to 10% or more stones* (cm)

Percent stones is a visual estimate of volume.

X_{25-33} *Depth to 20%, 30% ---- 100% stones* (cm)

As for X_{24}

X_{34} *Depth to horizon with highest clay content (cm)*

Clay content determined by field test.

X_{35} *Depth to horizon of highest increase in clay content* (cm)

As for X_{34}.

X_{36} *Effective rooting depth* (cm)

For definition see para. 2.6.2.1

2.3.1.3 **Other soil morphological factors**

X_{37} *Volume of stones in A 1 horizon* (%)

A visual estimate of volume of stones in the horizon sampled for chemical analysis.

X_{38} *Volume of stones in A* (%)

X_{39} *Volume stones in B (%)*

X_{40} *Volume stones in solum* (%)

X_{41} *Geology*

Coded as	1	=	Black Reef Formation
	2	=	Selati Formation
	3	=	Timeball Hill Formation
	4	=	Diabase
	5	=	Oaktree Formation
	6	=	Granite
	7	=	Dolomite Formations

X_{42} *Weathering*

Weathering of parent material was coded on the scale of 1 = slightly weathered, 2 = partially weathered, 3 = highly weathered.

X_{43} *Soil structure of B horizon*

Coded as 1 = apedal porous, 0 = other types of structure.

X_{44} *Permeability*

Recorded for the surface horizon as

1	=	gradual
2	=	moderate
3	=	moderately rapid
4	=	rapid

Soil Colour ex Munsell colour charts (Munsell Color Division, 1975):

X_{45} *A horizon : Hue*

Coded as	2	=	10R
	3	=	1,25 YR
	4	=	2,5 YR
	5	=	3,75 YR
	6	=	5 YR
	7	=	6,25 YR
	8	=	7,5 YR
	9	=	8,75 YR
	10	=	10 YR
	11	=	1,25 Y
	12	=	2,5 Y

This coding was used by Evans (1971) and Grey (1978).

X_{46} *A horizon : Value*
As recorded

X_{47} *A horizon : Chroma*
As recorded

X_{48}-X_{50} *B horizon*
As for A horizon

2.3.2 SOIL ANALYTICAL FACTORS

These are parameters requiring collection and laboratory analysis of soil samples (variables X_{51} to X_{100} in Table 2.2). Soil samples were extracted from the A 1 and B 21 horizons from the 3 extremities of the L of the soil pit and bulked. In addition a bulk surface sample to a fixed depth of 15 cm was taken from 20 points on diagonal lines across the plot. Standard control procedures were employed in the laboratory analyses. Results were carefully scrutinized and the samples returned for re-analysis in doubtful or unexpected cases. Many samples were re-analysed more than once, some several times, until final satisfaction was obtained.

2.3.2.1 **Texture**

The method of particle size analysis is described in Appendix 7.1. Independent variables were the following:

X_{51} *A 1 horizon clay* (g 100 g^{-1})

X_{52} *A 1 horizon silt* (")

X_{53} *A 1 horizon clay + silt* (")

X_{54} *A 1 horizon total sand* (")

X_{55} *A 1 horizon fine sand* (as a proportion of *total sand*)(g 100 g^{-1})

X_{56} *A 1 horizon medium sand* (g 100 g^{-1})

X_{57} *A 1 horizon coarse sand* (")

X_{58-64} *B 21 horizon* As for X_{51-57}

2.3.2.2 Bulk density

Bulk density was determined for the surface horizon and the most dense following horizon. Stony horizons were not sampled. Samples were extracted from the sides of the soil pit with a bulk density cylinder of volume 98,8 cm^3. Bulk density was calculated by the following formula:

$$\frac{\text{total mass of sample (kg) - mass of stones (kg)}}{\text{total volume of sample (m}^3\text{) - volume of stones (m}^3\text{)}}$$

Possible reasons for the low bulk density values (Table 2.2) have already been discussed (Ch. 1, para. 1.5.1). The following independent variables incorporated bulk density:

X_{65} *Surface bulk density* (kg m^{-3})

X_{66} *Subsurface bulk density* (kg m^{-3})

X_{67} *Ratio surface to subsurface bulk density*

X_{68} *Depth to highest bulk density* (cm)

2.3.2.3 Chemical

Nitrogen
This was not determined in view of the technique problems. In reviewing laboratory testing methods for available N in forestry, Keeney (1980) has concluded that considerable research effort will still be required before a reliable method of estimating available N can be found.

Available phosphorus
The extractant used was Bray 2. The method is described in Appendix 7.2.

Exchangeable bases
Exchangeable K, Ca and Mg were extracted using the method described in Appendix 7.3. Na was not determined as samples from 10 representative sites taken during the land type survey (Schoeman *et al*, 1980) confirmed what was

expected, viz. that in such a high rainfall area available Na would seldom exceed 0,1 mg kg^{-1}.

Exchangeable aluminium

The method of analysis is described in Appendix 7.4.

Independent variables arising from the above were the following:

X_{69} *A 1 horizon P* (mg kg^{-1})

X_{70} *A 1 horizon K* (")

X_{71} *A1 horizon Ca* (")

X_{72} *A 1 horizon Mg* (")

X_{73} *A 1 horizon Al* (cmol (+) kg^{-1}

X_{74-78} *B 21 horizon*
As for X_{69-73}

X_{79-83} *Bulk surface fixed depth sample*
As for X_{69-73}

Organic carbon

The method of analysis is described in Appendix 7.5.

pH in water and in KCl

This was done in a 1: 2,5 soil-water suspension according to standard methods (FSSA, 1980), using Beckman electrodes and a Metrohm Titriskop E-516 pH meter.

Exchange acidity

The procedure is described in Appendix 7.6.

Independent variables arising from the above were the following:

X_{84} *A 1 horizon organic carbon* (%)

X_{85} *A 1 horizon pH (KCl)*

X_{86} *A 1 horizon pH (H_2O)*

X_{87} *A1 horizon exchange acidity* (cmol (+) kg^{-1})

X_{88-90} *B21 horizon*
As for X_{85-87}

2.3.2.4 **Sum of exchangeable bases**

From the analyses described above, the following combination of elements were calculated for testing as independent variables for A 1 and B 21 horizons:

X_{91-92} *Sum of exchangeable bases (cmol (+) kg^{-1} soil)*
Exchangeable *K* + *Ca* + *Mg* expressed in cmol (+) kg^{-1} soil. This variable probably approximates the S-value although Na was not included, as Na levels were expected to be extremely low.

X_{93-94} *Sum of exchangeable bases (cmol (+) kg^{-1} clay)*
Exchangeable *K* + *Ca* + *Mg*, as above, for clay.

X_{95-96} *Effective CEC* (cmol (+) kg^{-1})
Sum of exchangeable bases (soil) plus exchange acidity.

X_{97-98} *Base status*
Sum of exchangeable bases (soil) ÷ *effective CEC.*

X_{99-100} *Aluminium saturation (%)*
Exchangeable aluminium ÷ effective CEC, expressed as a percentage.

2.3.3 BIOLOGICAL FACTORS

These factors do not have much value as independent variables for site index prediction, but where quantifiable they can be of use in explaining some of the variation in the total sum of squares not accounted for by site factors.Biological factors which can be quantified are usually those classed as "stand factors", although not all are easily quantifiable.

2.3.3.1 Seed source

The history of the introduction of *P.patula* into South Africa has been described by Poynton (1979). Details of seed source were given by Burgers (1975). Seed sources for 106 of the *P. patula* plots could be traced (Table 2.3). All collections were from local (S.A.) sources, most of them mixed. None appear to originate from stands established from the original importations of seed described by Burgers (1975). Even these stands showed botanical characteristics covering nearly the whole range of variations of the Mexican provenances, making identification of seed source difficult (Burgers, 1975). Major differences between stock numbers after the first generation therefore appear unlikely. Differences between stock numbers for mean top height at 20 years were also negligible. Stock number in the case of *P. patula* was therefore not considered further.

Table 2.3 Source of seed for *P.patula* stands surveyed

Stock no.	Source	No. of plots
2681	Berlin and Coetzeestroom, 1939	10
2686	Berlin - 8 compartments, 1941	3
2689	Berlin - 3 compartments, 1942	3
2691	Berlin - 1 compartment, 1943	1
2694	Berlin - 6 compartments, 1944	1
6788	Kologha - 1 compartment, 1930	2
7097	Woodbush, Belfast, Graskop, Jessievale, Berlin, De Hoek (mixture)	56
9439	Graskop, Belfast, Jessievale, 1928	4
9978	Graskop - 1 compartment, 1930	6
9982	Spitskop - 10 compartments, 1945	5
9985	Spitskop - 3 compartments, 1946	6
11935	Weza - 1 compartment, 1946	3
12027	Coetzeestroom - 2 compartments, 1948	1
13853	Tweefontein - 5 compartments, 1947	5
	Total	106

2.3.3.2 Other stand factors

These include *stand age*, *present stand density* and *stand density at 20 years* (the standardized age of the dependent variable was 20 years). *Mean D.B.H*, *mean tree height*, *mean volume*, *form factor*, *bark thickness* and *total* and *mean basal area* were additional variables recorded which could influence other dependent variables in this study, e.g. wood properties. The standard Directorate of Forestry equation was used for volume calculation of *P. patula*:

$$\log \text{volume (u.b.)} = -5{,}84966 + 2{,}43963 \times \log(\text{DBH o.b.} + 8) + 1{,}32537 \log \text{ht}$$

where u.b. = under bark
o.b. = over bark
DBH = diameter breast height, cm
ht = height (m)

2.4 DEPENDENT VARIABLES

There are several possibilities when selecting an index of tree growth in a site-growth study. The forest manager's interest is in the influence of site on volume yield. In site-growth studies, however, *volume* is not normally used as a dependent variable as it is so strongly influenced by stand density and thinning regime. Instead *top height* is used, as it is the parameter most sensitive to site and least affected by stand density, while generally having a good correlation with volume.

There are several definitions of *top height*. A commonly used one is the mean height of a fixed percentage of the trees with largest D.B.H. (Rennolls, 1978). This is usually 10%, but in this study the stocking density in many plots was so low that a 10% sample would have provided less than 10 trees for calculation of a reliable mean, unless the already large plot size of 0,1 ha had been increased. A lower *top height*, defined as the arithmetic mean height of 30% of the trees with largest D.B.H., had therefore to be accepted in order to provide 10 trees per plot.

Top height at 20 years is a standard index age for pines in South African forestry. Due to normality problems in the management of the Eastern Transvaal plantations, the age class distribution was heavily skewed in the direction of the older age classes (mean age 38 years). Two questions arose in estimating height at 20 years from stands as old as 38 years and more:

(i) Would the trees of largest D.B.H. selected at 40 years for calculation of *mean top height* also have been the trees of largest D.B.H. at 20 years? If not, one could have little confidence in the figure for *top height* at 20 years.

(ii) How accurately can the height of trees at 20 years be estimated from trees as old as 38 years? These problems were dealt with as described below.

2.4.1 LARGEST D.B.H. TREES AT 38 YEARS vs. 20 YEARS

The existence in the study area of a Correlated Curve Trend (C.C.T.) thinning experiment (Bredenkamp, 1984) with detailed records made it possible to trace the D.B.H.'s and heights of individual trees from ages close to those of the sampled stands back to 19 years (the age closest to 20 years when an enumeration had taken place), and over a range of stocking densities.

The differences in 30% *top height* at 19 years between the largest D.B.H. trees selected at a late rotation age and the largest D.B.H. trees selected at 19 years in the Mac Mac C.C.T. are given in Table 2.4.

Table 2.4 Differences in 30% *top height* (ht) at 19 years between largest D.B.H. trees selected at approximate site survey mean age (A), and largest D.B.H. trees selected at 19 years (B). (Mac Mac C.C.T. data).
(Site survey data: Mean age 38 years, mean N ha^{-1} 335, range 210 - 540 N ha^{-1})

Plot no.	Present N ha^{-1}	A. *Top ht* (m) ex 38 yrs	B. *Top ht* (m) ex 19 yrs	Difference (m)
5	247	24,7	24,7	0,0
6	321	24,2	24,1	+0,1
12	247	22,6	23,2	-0,6
14	470	24,0	24,3	-0,3
15	321	25,1	24,9	+0,2
17	346	24,3	24,0	+0,3
18	247	24,0	23,9	+0,1

It was not possible to test these comparisons in plots of stocking densities less than 235 N ha^{-1}, as too few trees were available for calculation of a reliable mean. Nevertheless there is sufficient evidence to suggest that the consequences of selecting the largest D.B.H. trees at a late rotation age instead of at 20 years for calculation of 30% *top height* would not be serious. The maximum error of 0,6 m is slight considering the wide range in *top height* at 20 years over all sites (13,8 - 32,9 m) (Table 2.5).

2.4.2 ESTIMATION OF TOP HEIGHT AT 20 YEARS FROM LATE ROTATION TOP HEIGHT

Top height at 20 years would normally be estimated from site index curves (para. 2.1.3) if they were available for the specific locality of the survey. Such curves do not exist for the Eastern Transvaal. Extrapolation/interpolation from site index curves for a wider region (these are available for the whole of South Africa) would be less accurate. One would also have less confidence in estimations of height at 20 years using height measurements of stands as far removed from the index age as 38 years and older. In most site studies, site index curves are constructed either from complete stem analyses (Carmean, 1975) or from hypsometer measurements of present height (Grey, 1978). Complete stem analysis of some 1600 very large trees (mean age 38 years) in the Eastern Transvaal was considered impractical, as was the height measurement by hypsometer of such old trees with rounded crowns. Instead a method of direct measurement of the height at 20 years was employed. Trees were selected and measured as follows:

The 30% largest D.B.H. trees on a plot were selected. If the number of trees selected was less than 10, the balance was obtained outside the plot and as close as possible to it. This occurred only in plots with very low stocking, and in practice a maximum of two trees had to be selected outside the plot. If 30% of the trees on the plot was more than 10 in number, then 10 of this number were selected at random, the object being to ensure that there would be an equal chance of selecting the same 10 trees regardless of stocking. This is not equivalent to selecting the 10 largest trees per plot, as these would not necessarily be the ones to remain after a final thinning. In practice large trees are frequently removed in final thinning as *P. patula* often has bad form. The 10 sample trees were felled. The height which a tree was assumed to have attained at 20 years was located by cutting through the bole at the point where the number of annual rings found was the present age minus 20 (Fig. 2.2).

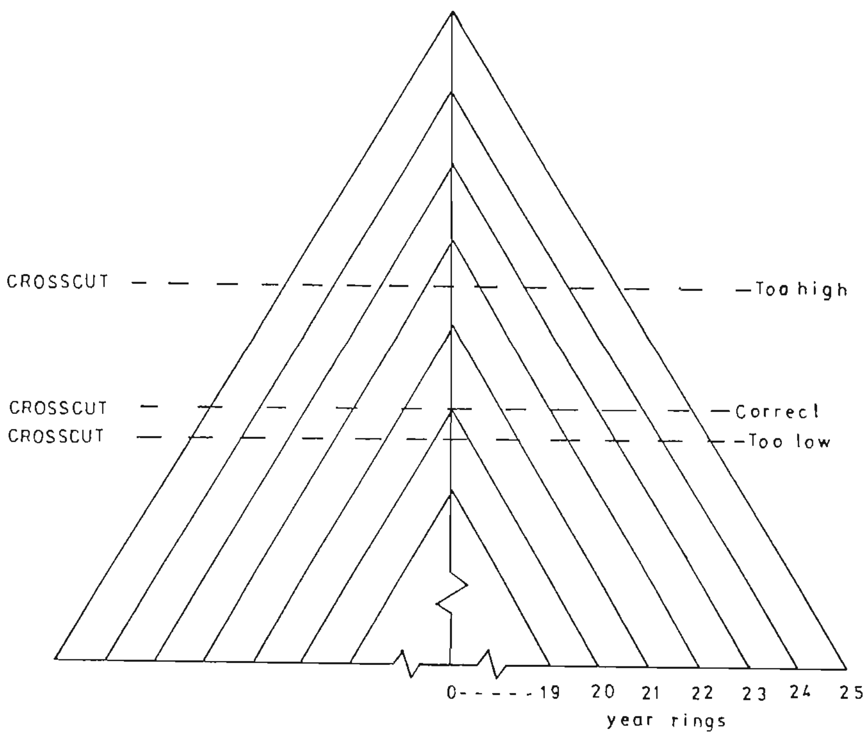


Figure 2.2 Determination of height at 20 years

In practice this point could be located with a surprising degree of accuracy, after only two or three cross-cuts. It was possible to locate the 20-year point within 20 cm of the true height at 20 years (Fig. 2.2), assuming the rings to have been correctly counted. The fact that trees on all 159 plots were felled within a three-week period (in June) facilitated the standardization of this procedure. As trees had always been planted in the rainy season, height determination in June meant that the actual age was between 20 yrs 2 months and 20 yrs 8 months. This error was not regarded as serious as that which might have arisen had the trees not been felled in June. Planting dates had been recorded in two different ways, for example 1/42 (= January - April 1942), 2/42 (= October - December 1942), or 42/43 (= October 1942 - April 1943). For 1/42 the planting date was taken as 1942, for 2/42 1943 and for 42/43 also 1943. Having located the 20-year point, tree height was measured with a tape, adding stump height. The arithmetic mean of the 10 tree heights was then calculated.

Confidence in these measurements is further enhanced by the fact that they are based on felled tree measurements rather than hypsometer measurements of standing trees, which can frequently be inaccurate. Furthermore, few site studies have used as many as 10 trees for calculation of *mean top height*.

2.4.3 CHOICE OF DEPENDENT VARIABLE

Top height at 20 years as described above is only one of several parameters of tree growth which could be used as the dependent variable. The possibilities which were investigated were the following:

Y_1 *Top height at 20 years* based on the mean of 10 trees ($HT20_{10}$)
As described above.

Y_2 *Top height at 20 years* based on the mean of 5 trees ($HT20_5$).
If it were possible to obtain a reliable estimation of top *height* from the mean of fewer than 10 trees per site, the costs of future site-growth surveys would be less. Of the 10 trees selected for calculation of Y_1, the 5 largest in diameter were taken for calculation of Y_2. This corresponds approximately to a 17% *top height* as opposed to 30% for Y_1.

Y_3 *Regression height at 20 years* ($HT20_R$)
Top height at 20 years can be estimated from current top height using a suitable site index regression equation, also with cost advantages. The

following regression equation was used for this purpose:

$$\log \text{site index} = \frac{-0{,}1778 + \log \text{ht} + (3{,}55 \times 1/\text{age})}{0{,}9998}$$

(Bredenkamp, pers. comm.)

Y_4 *Mean annual height increment at 20 years* ($HT20_{MAI}$)
There is a possibility that competing vegetation could have affected the early growth of trees more severely on some sites than on others, to the extent that the height at 20 years would not be a true reflection of site potential. It was assumed that competing vegetation would not affect the height increment of a tree after it had reached a height of 3 m. The bole was therefore cut through at 3 m and the number of years which the tree took to reach this point was estimated from ring counts. The mean annual height increment from the age at 3 m to 20 years (using *HT20*) was then calculated for each tree and averaged over the 10 sample trees.

Y_5 *Top height at 30 years* ($HT30_{10}$)
Calculated in the same way as Y_1, this variable is of interest mainly in comparison with Y_1 to determine whether the relative importance of site factors change as stands grow older.

Y_6 *Top height at 40 years* ($HT40_{10}$)
This was calculated from current top height using the same equation as in the case of Y_3.

Y_7 *MAI 20 index* ($V20_{MAI}$)
This is an estimate of volume increment at 20 years and has the advantage of taking into account the effect of site on diameter as well as on height. It is derived from a model constructed by the Management Section of the Forestry and Environmental Conservation Branch, based on the Mac Mac C.C.T. experiment which is located within the study area. The model uses a standard thinning regime, with inputs of current D.B.H., mean height and thinning history. However, two problems have arisen in the use of *MAI 20 index* in this study:

The first is that whereas *mean stand height* is required as an input for the model, only 30% *top height* is available in this case, thus leading to an inflation of the *MAI 20 index* figure. This is not regarded as a serious problem, however, as it is the *relative* differences between sites which are important. The second problem is the paucity of records on stand history in the area. The thinning history for 15 out of 159 plots could not be traced. An attempt was made to estimate the missing data from the thinning history of adjoining compartments, but when tested against site factors the *MAI 20 index* thus calculated was found to have much lower correlations with site factors than when based on the fewer plots with complete data. Missing plots were therefore dropped when Y_7 was used.

Y_8 *Total basal area (TBA)*
This parameter has been used in site studies, but rarely (Meeuwig and Cooper, 1981; Turvey *et al*, 1986).

Y_9 *Mean basal area (MBA)*
As for Y_8

Summary statistics for the above dependent variables are shown in Table 2.5.

Table 2.5 Summary statistics for dependent variables

No.	Variable	Units	Mean	Range	Std.Dev.	c.v %
Y_1	$HT20_{10}$	m	23,8	13,8 - 32,9	4,02	17
Y_2	$HT20_5$	m	24,2	14,3 - 33,3	4,10	17
Y_3	$HT20_R$	m	25,0	16,6 - 34,3	3,84	15
Y_4	$HT20_{MAI}$	m yr^{-1}	1,21	0,63 - 1,73	0,214	18
Y_5	$HT30_{10}$	m	27,8	16,6 - 37,3	4,39	16
Y_6	$HT40_{10}$	m	30,3	20,4 - 42,1	4,96	16
Y_7	$V20_{MAI}$	m^3 yr^{-1}	18,78	8,87 - 39,90	0,14	33
Y_8	*TBA*	m^2 ha^{-1}	29,6	16,5 - 46,1	5,53	19
Y_9	*MBA*	cm^2 $tree^{-1}$	1353	881 - 2606	271	20

The problem that now remains is the selection of the dependent variable most sensitive to site and least sensitive to other influences. This can only be done by testing each dependent variable in regression analyses, but a preliminary choice must nevertheless be made at this stage to enable regression methods to be tested and finalized. It was decided that Y_1

($HT20_{10}$) offered the best potential, as it was based on a direct measurement of the maximum number of sample trees. For the purposes of this study Y_1 is defined as *site index*.

2.5 REGRESSION ANALYSIS

Linear regression analysis based on the method of least squares provides a simple method of establishing a functional relationship among variables (Cox, 1984 a). The multiple linear regression model takes the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \text{------} \beta_p X_p + \epsilon$$

where Y is the dependent variable, β_0 is the intercept term, β_1, β_2, ... β_p are the regression coefficients, X_1, X_2, ... X_p are the independent variables or predictors, and ϵ is a random variable drawn from a normal distribution, with zero mean and constant variance. The term 'linear' governs 'regression' and not 'model', i.e. the model is linear in the parameters β_0 β_1 ... β_p, not because Y is a linear function of the X's. The regression coefficient β_i may be interpreted as the increment in Y corresponding to a unit increase in X_i when all other variables are held constant. The regression coefficients are estimated by minimizing the sum of squared residuals, which is known as the method of least squares.

It is important (from a statistical point of view) that the independent variables be measured without error, or that such errors be minimal in comparison with those in Y. It is also necessary to bear in mind that the X's in the model are not necessarily the cause of variation in Y, only that in terms of the data available, the observed changes in Y are related to, or correlated with the X's in a strictly statistical sense.

The lack of clear guidelines in the choice of regression techniques can be a problem for the analyst (Snee, 1983; Cox, 1984 b). Snee attempts to remedy this with an outline of some essential elements of a regression analysis, and recent case studies are certainly an aid, but as so much depends on the objectives in view and on the nature of the data, it is doubtful that it will ever be possible to come up with a fixed recipe (Hocking, 1983). The fitting of equations to data is not straightforward, and extreme caution and common sense when scrutinizing the data are advised by Hocking. Snee (1983) advocates the following "reasonableness tests" at each step in the analyses:

1. Do the results make sense in the context of the problem?
2. Are the results reasonable?
3. Are the results believable?
4. Would a non-statistician be able to understand and use the results?

A blind, mechanical application of existing procedures is to be avoided at all costs. It must be strongly emphasized that what is uncovered along the way to the formulation of an equation may often be as valuable and informative as the final equation itself.

In view of the large number of independent variables in this study, it was decided to split the data into two sets for separate analysis, viz., field-measurable variables and soil analytical variables. The most promising variables identified by each regression analysis were then combined for derivation of a full model. The procedures described for construction of the field model would also serve as a basis for the derivation of all subsequent models in subsequent chapters. Discussion of the site factors appearing in the different models and their possible role in influencing site index will take place in para. 2.6.

The bulk of the analyses were performed using the computer package REGPAC version 3 (Galpin, 1981). REGPAC is a powerful regression package developed by the National Research Institute for Mathematical Sciences of the C.S.I.R., Pretoria. Its main advantage is the best-subsets regression programme, which is superior to most other packages. All REGPAC computations were run at double precision. The SAS package (SAS Institute, Inc., 1985) was used for Cluster, Principal Components and Factor Analyses, and for the creation of dummy variables.

2.5.1 FIELD-MEASURABLE VARIABLES

2.5.1.1 **Preliminaries**

Summary statistics

Summary statistics (mean, standard error, standard deviation, variance, kurtosis, skewness, range, minimum, maximum, sum) were obtained for each variable as a check on the data for errors. (Some of these statistics were shown in Table 2.2). Ranking of the observations for each variable also proved a useful exercise, especially in tracing outliers.

Correlations

To gain some indication of relationships among variables a correlation matrix was obtained. Pearson product-moment correlation coefficients (r) greater than 0,30 between field independent variables and *site index* (top height at 20 years) are shown in Table 2.6.

Table 2.6 Correlation coefficients (r) > 0,30 between *site index* and field independent variables

No.	Variable	r
X_3	*Rainfall*	-0,48
X_4	*Altitude*	-0,63
X_9	*Slope position Chorley*	0,38
X_{10}	" " *Conacher*	0,38
X_{11}	" " *Local 1*	0,45
X_{12}	" " *Local 2*	0,46
X_{20}	*Thickness B hor.*	0,52
X_{21}	" *Solum*	0,51
X_{23}	*Depth fine roots*	0,44
X_{25}	" *≥20% stones*	0,41
X_{26}	" *≥30%* "	0,48
X_{27}	" *≥40%* "	0,59
X_{28}	" *≥50%* "	0,54
X_{29}	" *≥60%* "	0,44
X_{30}	" *≥70%* "	0,44
X_{31}	" *≥80%* "	0,39
X_{32}	" *≥90%* "	0,41
X_{33}	" *100%* "	0,38
X_{39}	*Vol. of stones B hor.*	-0,37
X_{40}	" " " *Solum*	-0,35
X_{41}	*Geology*, coded	0,66
X_{42}	*Weathering*	0,65
X_{48}	*Hue B hor.*	-0,46
X_{50}	*Chroma B hor.*	0,34

P < 0,0001 in all cases
n = 159

Not a great deal of reliance can be placed on bivariate correlation coefficients to reveal important relationships. In a multiple regression situation an apparent correlation between two variables may instead be due to the influence of other variables or conversely, an apparent low correlation may in fact be a strong relationship obscured by the influence of other variables. Nevertheless variables which are highly correlated with the dependent variable stand a good chance of being included in the regression model and should therefore be watched closely during the analysis procedure. Promising variables in Table 2.6 were therefore *geology*, *weathering*, *altitude* and *depth to ≥40% stones*.

Also of interest is the sign of the correlation coefficient. Thus the negative coefficient for *altitude* indicates that *site index* improves with decreasing *altitude*, as it does with decreasing *rainfall*. (The latter apparently anomalous relationship will be discussed later). The negative sign for *volume of stones* was not unexpected as coarse fragments reduce rooting volume in the soil. The inverse relationship for *B horizon hue* could indicate that *site index* is lower on yellow than on red subsoil.

Scatter diagrams

Scatter diagrams of *site index* on the independent variables were obtained. The inadequacy of scatter diagrams in analysing the relationship between Y and X for more than one X is described in most text books, e.g. Montgomery and Peck (1980, p.122), the same objections applying as in the case of correlation coefficients. Nevertheless Snee (1983) recommends exploratory plots to aid model formulation, and for this purpose they did prove to be of use, as will be discussed later. Scatter diagrams were also useful in checking outliers for correction of obvious errors at an early stage.

Obvious transformations and interactions

Aspect is usually recorded as an azimuth clockwise from north, but since forest growth is frequently greater at an aspect different from north, greater weight should be assigned to the best one. Various proposals for transformation of aspect in site index studies have been suggested, reviewed by Stage (1976). In this study the scatter of points in the scatter diagram was such that it was impossible to locate the optimum aspect. Grouping of the data into 8 classes (N, NW, W, SW, etc.) did not help. The sine and cosine transformations as usually proposed (Beers *et al*, 1966; Stage, 1976) were then applied and employed as independent variables in addition to untransformed *aspect*.

Few site studies have considered the obvious interaction between aspect and slope. Plots on level ground supply no information on the effect of aspect on tree growth, while it can be assumed that the effect of aspect will increase on an adverse aspect up to the angle of slope that is perpendicular to the sun's rays. Stage (1976) recognized this problem and proposed a method employing two multiple regression equations to calculate amplitude, phase shift and the combined effect of aspect and slope on tree growth. A cosine function is used in the second equation. In this study, however, a sine function was tested as well, assuming that the situation in the southern hemisphere might be different.

Discarding variables

One way of reducing the large number of independent variables (Table 2.2) prior to regression analysis is to avoid the unnecessary inclusion of groups of variables expressing similar site influences where only the "best" one of the group is required. There would, for example, be no point in having a model which might include more than one system of classifying *slope position*. Only the most appropriate one is sought. This was achieved by running preliminary regression analyses including each one of the coded *slope position* systems separately (X_9 - X_{12}). The *local model no. 2* (X_{12}) emerged as the system having the closest relationship with *site index*, confirming the highest correlation coefficient of the group (Table 2.6). Similarly, of the *depth to stones* group (X_{24} - X_{33}), *depth to ≥40% stones* emerged as the best variable, also confirming the correlation coefficient.

Qualitative variables

The handling of qualitative or categorical variables in multiple regression analysis has long been regarded as a problem in forestry. Many workers have tried to avoid their use altogether, thereby possibly missing an important factor, or have tried to substitute quantitative variables which express a supposedly similar effect, e.g. soil water and nutrient levels in place of topographic position. In this example, as in many others, the alternative may prove more costly to measure and may not necessarily express all the influences which may be conveniently reflected in the qualitative variable.

In most cases qualitative variables are allocated codes, based either on their expected influence on tree growth (e.g. *slope shape* commonly coded as 1 = convex, 2 = straight, 3 = concave), or on their measured effect as reflected by the mean of the dependent variable for each category, the means then being ranked and assigned a code reflecting the ranks, as was done in the case of *geology* (X_{41}, para. 2.3.1). Montgomery and Peck (1982, Ch. 6) point out the dangers of this approach. Amongst others, the supposed or measured effect may in fact be due to the influence of other factors, the same objections applying as in the case of simple correlation coefficients. The allocated codes also usually assume that the treatment effects are equally spaced, when in a multiple regression situation this would be highly unlikely. Nevertheless this technique has been widely used for expressing slope shape (Graney, 1974), topographic position (Hardcastle, 1976), soil colour hue (Evans, 1971), soil parent material (Grey, 1978), soil type (Evans 1971), and other factors. Grey (1978) used the technique for soil series but expressed misgivings.

The system of dummy (or indicator) variables to cope with the problem of quantitative predictors has long been in use in other disciplines and is well described in text books (Draper and Smith, 1981, Ch. 5.4; Chatterjee and Price, 1977, Ch. 4; Montgomery and Peck, 1982, Ch. 6). A set of dummy variables is created by treating each category of a qualitative variable as a separate variable and assigning arbitrary scores for all cases depending on their presence or absence. One of the categories (any one) is assigned all zeros and is called the reference category (Table 2.7) (There are, however, also other methods).

Table 2.7 Dummy variable values for *geology* (X_{41}).

	Dummy variable titles					
Categories	D1	D2	D3	D4	D5	D6
Quartzite	1	0	0	0	0	0
Selati	0	1	0	0	0	0
Timeball Hill	0	0	1	0	0	0
Diabase	0	0	0	1	0	0
Oaktree	0	0	0	0	1	0
Granite	0	0	0	0	0	1
Dolomite	0	0	0	0	0	0

In the above table *Dolomite* is the reference category, for no reason other than that it is the last one. These values are then entered in multiple regression analysis as independent variables. The reference category is simply omitted as it is zero. The regression coefficient for the first dummy variable in the equation is the difference in predicted Y between the reference category and category 1, the second coefficient is the difference in predicted Y between the reference category and category 2, and so on, with all other variables kept constant. Qualitative variables showing an appreciable effect may also be split for separate analysis of each category, especially where the variances are not equal (if there are sufficient observations in each), or kept together as a group in one equation (Montgomery and Peck, 1982, p.224). The advantages of the dummy variables approach are that it does not require the analyst to make any prior assumptions about the functional form of the relationship between the qualitative variable and the dependent variable, and that it always leads to a larger R^2 than does regression on allocated codes (Montgomery and Peck, 1982, Ch. 6). The use of dummy variables in forestry has received little attention and has usually been confined to variables with only two categories, e.g. presence or absence of B horizons (Grey, 1978). Page (1976) used dummy variables for soil type, drainage class and geology to predict growth of spruce and fir in Newfoundland, but split his categories for separate analysis. However, Moosmayer and Schöpfer (1972) included dummy variables for soil type and other factors in a single regression equation for spruce in Europe. Vincent (1980) did the same for *P. caribaea* with respect to topographic position.

In this study the following variables were expressed in dummy variable format for the purpose of regression analyses:

slope shape	(X_8)
slope position	(X_{12})
geology	(X_{41})
structure	(X_{43})
hue, A hor.	(X_{45})
hue, B hor.	(X_{48})

In the case of *slope shape* and *slope position* there is a rough ordinal basis for the allocation of codes, as opposed to the other qualitative variables. Nevertheless it was found that expression of qualitative variables in dummy variables format increased R^2 over regression on allocated codes in every case, and usually changed the ranking of the categories as well.

2.5.1.2 **Variable selection**

A regression model should on the one hand include a sufficient number of independent variables to explain a substantial portion of the variability in Y, but on the other hand as few as possible, as the variance of the prediction $\hat{Y}$ increases as the number of predictors increases, and the costs of data collection and model maintenance need to be kept as low as possible. The process of finding a model that is a compromise between these two objectives is called selecting the "best" regression equation (Montgomery and Peck, 1982 p.245). Unfortunately there is no definition of "best", and not a single "best" equation but rather several equally good ones. Box, quoted by Snee (1983), goes so far as to state that "all models are wrong, but some are useful". The problem of variable selection is the aspect of regression that causes most concern in application, and is still being researched (Cox, 1984 b).

Correlation coefficients

Before the advent of suitable variable selection techniques in regression packages, bivariate correlation analysis was often employed as an initial guide to the selection of variables for inclusion in the regression model (e.g. Della Bianca and Olsen, 1961; Evans, 1971; Graney, 1974). The dangers of this procedure have already been stressed in para. 2.5.1.2. Simple correlation coefficients can only be used for variable selection in the case of univariable regression, the best equation with one variable being that which includes the single variable with the highest correlation coefficient.

Correlation coefficients are often used as indicators of multicollinearity, one of two highly correlated variables being selected for inclusion in regression analysis, the other being discarded. For the same reasons outlined previously, this test for multicollinearity can be misleading. The problem is in any case not as simple as collinearity between two variables, as multicollinearity usually exists among and between groups of variables, in which case detection is not simple. Most regression packages, however, have good tests for multicollinearity. The use of correlation coefficients in variable selection is thus not advisable.

Stepwise regression

Stepwise regression, with many recent variations on the theme, is a widely used procedure for variable selection. However, it should only be used with well-conditioned data (Hoerl *et al*, 1986) and there are other problems of which the user should be aware (Chatterjee and Price, 1977, p.203; Hocking, 1983). In this study stepwise procedures were compared with best-subsets regression and in a number of cases Stepwise failed to select some significant variables.

Principal Components Analysis

Multivariate techniques such as principal components analysis are often used to obtain a subset of orthogonal predictors for subsequent regression analysis, but the method has not always been successful (para. 2.1.3.4.). One of the problems is that important variables may be missed due to a small degree of multicollinearity which could be accommodated by ridge regression, for example. In this study principal components analysis was tested in the selection of variables for the full model (para. 2.5.3.1).

Best-subsets regression

A variable selection method which is gaining wider support is the "best-subsets regression" technique. Hoerl *et al* (1986), in a simulation study, found this method to be the most reliable. Some regression packages employ the "all possible regressions" method, but due to the large computational problems, the user is restricted to only a few variables. REGPAC employs the "leaps and bounds" algorithm of Furnival and Wilson (1974), which enables a specified number of only the "best" subsets to be evaluated, regardless of the number of variables. The user may specify the number of best-subsets, but the usual number is five of every subset size.

Mallow's *Cp* statistic (Daniel and Wood, 1980, p.86; Mallows, 1973) is used as a guide in selecting the appropriate subset size. The *Cp* statistic measures the performance of the variables in terms of the standardized mean square error of prediction, and takes into account both the bias and the variance (Chatterjee and Price, 1977 p.199). Bias occurs when an insufficient number of variables is included in the model (Draper and Smith, 1981, p.117). The selection of "good" subsets is done graphically. For the various subsets a graph of C_p is plotted against p (subset size) (Fig. 2.3). The line C_p = p is not drawn on the graph by REGPAC, but this is easily done by hand. Regression equations with little bias will have values of C_p that fall below the line C_p = p. Generally, small values of C_p are desirable. A weakness of C_p is that it is dependent on a good estimate of variance being available. This is usually obtained from the residual sum of squares from the full model. If the full model has a large number of variables with marginal contributions to the regression sum of squares, the estimate of variance would be biased upwards. If this estimate is large, then C_p is small and less efficient as a selection criterion (Montgomery and Peck, 1982, p.254).

Choice of a subset is not easy unless a uniquely best subset is indicated. As can be seen from Fig. 2.3, there are several small subsets which fall below the line *Cp* = p and close to it. As stated earlier, there is seldom a uniquely best equation but rather several equally plausible ones, particularly in the biological field. That this fact is acknowledged instead of a "blind reliance" being placed on some statistical test to select the "best" subset, is in fact one of the strengths of the procedure. The user is forced to resort to practical considerations for the final choice of a subset (Montgomery and Peck, 1982 p.282).

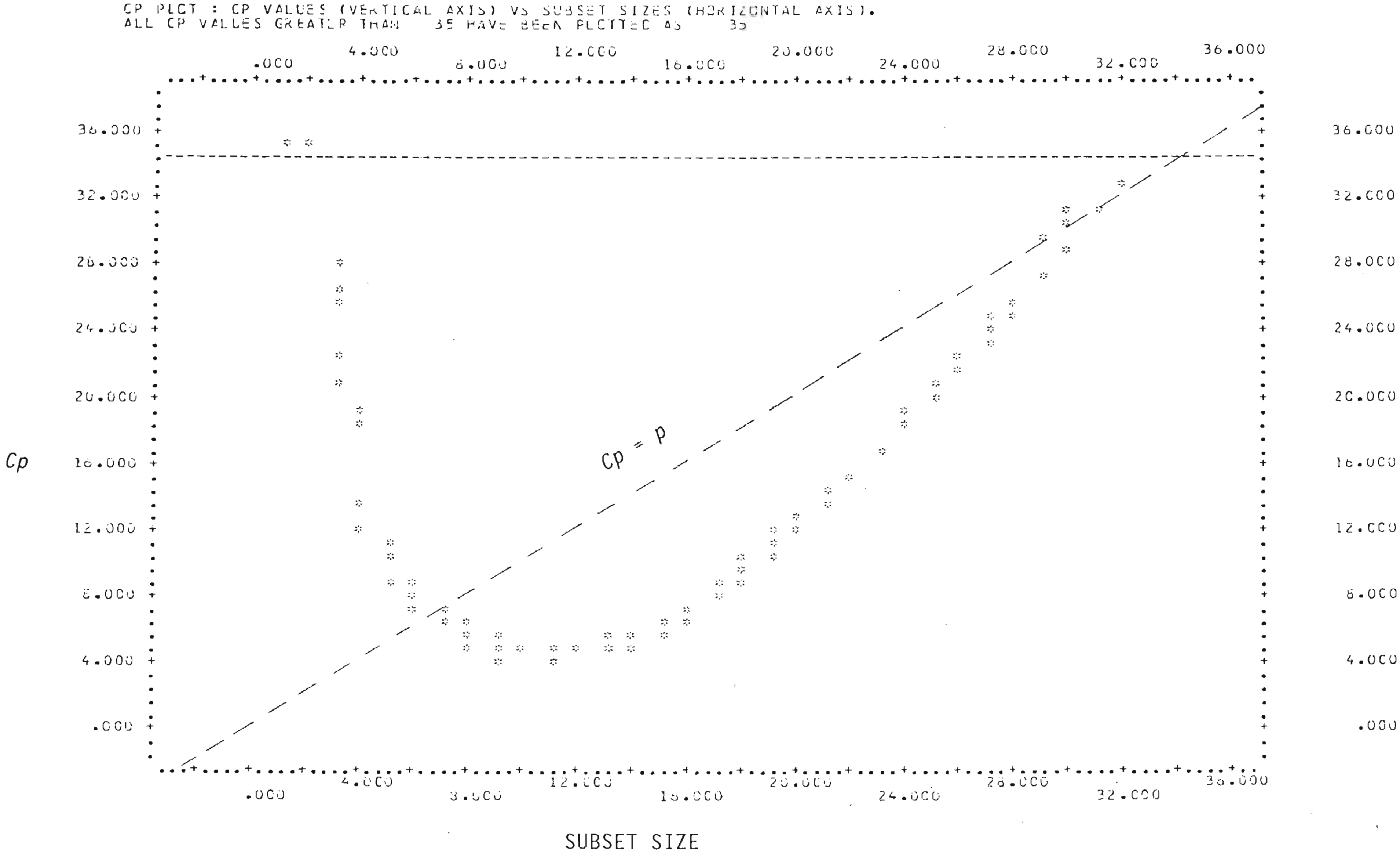


Figure 2.3 Cp plot. (Only the best of each subset size are plotted).

In this regard the best subsets printout of REGPAC (Table 2.8) is a powerful aid. Having determined from the C_p plot which subsets are the best candidates, the variables of each are studied in the printout. The final choice will be governed by considerations such as practicality, reliability and expense of measurement. The advantage of the best-subsets printout is that the effect of substitution, deletion or addition of variables can be seen at a glance. The best-subsets printout (Table 2.8) shows the subset size, R^2, adjusted R^2, residual sum of squares, C_p and the subset variables. The adjusted R^2 is more useful than R^2 when comparing subsets (Montgomery and Peck, 1982, p.251).

2.5.1.3. **Model building**

In this section regression models are presented in tabular form, showing the regression coefficients, their standard deviations, the standardized regression coefficients, the t-values of the regression coefficients and significance levels. For ease of reading, the number of decimal places are reduced except in the case of final models. The standard error of estimate (S.E.) and coefficient of determination (R^2) are also shown. In the tables, variables are ordered on the standardized coefficient, from largest to smallest. Standardized regression coefficients (Montgomery and Peck, 1982, p.170) give an indication of the approximate order of importance of the variables in the model, but this is only a rough guide, as there is no unique order of importance except in the case of orthogonal predictors (Hocking, 1983).

Similarly the use of standard significance levels in tests to determine the importance of a variable or whether a variable should be excluded from a model has recently been criticised (Hoerl *et al*, 1986; Mitchell, 1983). Formal significance tests are only approximate in regression analysis except in the case of orthogonal independent variables. Hoerl *et al* (1986) and other statisticians recommend significance levels between 15% and 25%. Schmidt and Carmean (1988) used a signifance level of 10% to select subsets of variables for prediction of jack pine site quality in Canada. Nevertheless, one would prefer a regression model to contain variables only with the highest possible levels of significance.

Using the techniques described in the preceding sections, a subset of variables was selected, the regression coefficients of which are shown in Table 2.9 (Model 2.1).

Table 2.8 Part of best-subsets printout (REGPAC)

BEST SUBSET REGRESSION,
USING CP CRITERION

PARTIAL RESULTS

SUBSET SIZE	R-SQUARED	ADJUSTED R-SQUARED	RESIDUAL SS	CP	VARIABLES					
1										
	0.4260	0.4222	86.674	329.265	LOGACA					
	0.4138	0.4099	88.517	339.413	LOGERD					
	0.2312	0.2260	116.093	491.260	AK					
	0.2203	0.2151	117.737	500.317	RAIN					
	0.2143	0.2090	118.647	505.326	AMG					
2										
	0.6203	0.6152	57.329	169.678	LOGERD	LOGACA				
	0.5101	0.5035	73.973	261.329	FSA	LOGACA				
	0.4942	0.4874	76.381	274.587	GOP4	LOGACA				
	0.4913	0.4845	76.812	276.962	RAIN	LOGACA				
	0.4776	0.4705	78.890	288.403	GOP2	LOGACA				
3										
	0.7117	0.7059	43.526	95.676	LOGERD	FSA	LOGACA			
	0.6628	0.6560	50.911	136.337	LOGERD	CLB	LOGACA			
	0.6569	0.6500	51.807	141.274	LOGERD	FIB	LOGACA			
	0.6436	0.6363	53.823	152.373	GOP4	LOGERD	LOGACA			
	0.6379	0.6306	54.674	157.058	LOGERD	ALTSQC	LOGACA			
4										
	0.7252	0.7178	41.489	86.457	GOP5	LOGERD	FSA	LOGACA		
	0.7229	0.7153	41.846	88.426	TSG1	LOGERD	FSA	LOGACA		
	0.7213	0.7137	42.091	89.774	TSG2	LOGERD	FSA	LOGACA		
	0.7184	0.7107	42.520	92.136	LOGERD	ALTSQC	FSA	LOGACA		
	0.7170	0.7093	42.736	93.326	CHRB	LOGERD	FSA	LOGACA		
5										
	0.7455	0.7368	38.427	71.595	GOP4	GOP5	LOGERD	FSA	LOGACA	
	0.7359	0.7268	39.882	79.609	GOP5	TSG1	LOGERD	FSA	LOGACA	
	0.7349	0.7258	40.029	80.418	CHRB	GOP5	LOGERD	FSA	LOGACA	
	0.7301	0.7209	40.750	84.387	GOP5	TSG2	LOGERD	FSA	LOGACA	
	0.7292	0.7200	40.887	85.141	GOP5	LOGERD	FSA	AP	LOGACA	
6										
	0.7576	0.7475	36.609	63.586	GOP4	GOP5	TSG2	LOGERD	FSA	LOGACA
	0.7547	0.7445	37.044	65.982	GOP4	GOP5	TSG1	LOGERD	FSA	LOGACA
	0.7543	0.7441	37.108	66.335	GOP4	GOP5	LOGERD	ALTSQC	FSA	LOGACA
	0.7527	0.7425	37.337	67.595	GOP2	GOP4	GOP5	LOGERD	FSA	LOGACA
	0.7479	0.7375	38.062	71.585	CHRB	GOP4	GOP5	LOGERD	FSA	LOGACA

Table 2.9 MODEL 2.1: Regression coefficients for the preliminary field model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Quartzite	-4,344	1,02	-0,26	4,27	0,00004
Selati	-3,134	0,99	-0,20	3,15	0,00197
Timeball	-2,091	0,81	-0,20	2,58	0,01091
Diabase	-2,171	0,84	-0,18	2,59	0,01056
Oaktree	-2,459	0,91	-0,16	2,72	0,00742
Granite	0,087	0,69	0,01	0,13	0,89985
Dolomite	0,000	(ref. cat.)			
Wide crest	-5,381	0,97	-0,47	5,57	<0,00001
Narrow crest	-4,232	1,01	-0,34	4,19	0,00005
Upper slope	-4,094	0,93	-0,42	4,41	0,00002
Mid slope	-3,431	0,85	-0,39	4,02	0,00009
Lower slope	-3,088	0,90	-0,29	3,45	0,00075
Foot slope	0,000	(ref. cat.)			
Altitude	-0,004	<0,01	-0,23	2,83	0,00530
B horizon thickness	0,015	0,01	-0,15	2,27	0,02477
Stone layer depth (depth $\geq$40% stones)	0,008	0,01	0,11	1,66	0,09922
Intercept	32,568	4,06			

R^2 = 0,6521 S.E. = 2,489

Transformations

Plots of residual vs. independent variables are used to identify any departures from linearity and the appropriate transformation necessary. No such problems were apparent from the residual plots. The scatter diagram for *altitude* against *site index*, however, did indicate a possible curvilinear relationship. As a similar trend in the *altitude-P.patula* growth relationship had been found in Swaziland (Evans, 1971), it was decided to test the introduction of a squared term for *altitude*. It proved to have a higher significance than the linear term and also increased the R^2. Squared terms for the other variables were also tested, but no improvement in the model resulted.

Following this trend of thought, it was decided to re- examine the plots for the soil depth variables *B horizon thickness* and *stone layer depth*. No departures from linearity were evident, not even in the bivariate scatter diagrams. However, as it is logical to assume that the influence of soil depth on tree growth would progressively decrease with increasing depth, it was decided to test log transformations. In the case of *stone layer depth* this transformation did indeed prove significant and improved the R^2.

One may conclude from this exercise that residual plots alone are not enough and that bivariate scatter diagrams, despite the problems described earlier, are useful supplements. However, as in the case of the soil depth variables, a certain amount of common sense is required. It should be stressed at this stage that any transformation of variables requires a re-run of the best-subsets selection procedure.

Interactions

Although residual plots did not reveal the existence of more than one level of residuals for any of the variables in the model, it was nevertheless decided to test interactions between the variables in multiple regression analyses. None proved significant.

Multicollinearity

In REGPAC (Galpin, 1981) multicollinearity is indicated by a harmonic mean of the eigenvalues greater than ten, the condition number of the X'X matrix greater than 100, or the presence of two or more almost equal, small (but non-zero) eigenvalues. Eigenvectors can be used to trace dependencies among the variables. The lowest eigenvalue for Model 2.1 was 0,07762, indicating that multicollinearity was within acceptable limits. (eigenvalues with two or more zeros after the decimal would indicate a problem). However, introduction of a higher-order term always results in a collinearity problem with the linear term. Thus when *altitude*^{2} was introduced, the lowest eigenvalue dropped to 0,00419 because of the presence of the linear term.

For polynomial models with squared or higher order terms, Snee (1983) and others recommend centring of the variables. This reduces the correlation between the linear and squared terms in the model. The variables were therefore centred by subtracting the mean value from each observation, and a multiple regression analysis was rerun to determine the new regression coefficients. The improved model increased the lowest eigenvalue to 0,07836, which is acceptable. The question arises whether it is necessary to include both the linear and the quadratic terms in the model. When the linear term was dropped, however, a less efficient model, with regard to R^2 and prediction, resulted.

Refining the *geology - site index* relationship

Differences in the effect on *site index* of the various rock types could not be tested statistically as the necessary hypothesis testing option is not available in REGPAC. From Table 2.9 it is noticeable that all the differences between *Dolomite* (the reference category) and the other geological substrates in Model 2.1 were highly significant except for *Granite*. Combining *Dolomite* and *Granite* into one category, however reduced the R^2. Although the reduction was slight, it was decided rather to retain *Granite* and *Dolomite* as separate categories for two practical reasons, viz. (i) soils derived from these rock types cover the largest surface area in the region, and (ii) they are spatially separated, i.e. other rock types intervene.

Also noticeable from Table 2.9 is the fact that the coefficients for *Timeball*, *Diabase* and *Oaktree* differ only slightly. As *Timeball* and *Oaktree* are spatially separated, combination of these two categories was not considered. However, diabase intrusions are found within all rock types. Diabase is difficult to locate in the field as it is seldom exposed and nearly always buried under a colluvial mantle originating from the adjacent rock type. Although a few large sills occur, diabase is found mostly in the form of narrow dykes occupying small areas spatially. Combining *Diabase* with the rock type into which it had intruded would therefore have definite practical advantages. With this adjustment to *geology*, best-subsets regression returned the same subset as before. But instead of the expected decrease in R^2 from combining classes, there was a slight increase. This can be taken as an indication that tree growth on diabase does not differ from that on the intruded rock type (a fact readily confirmed by visual observation in the field), and that retention of *Diabase* as a separate category is not warranted.

This line of thought leads one also to question the category *Quartzite*. Sites allocated to *Quartzite* included not only those on Black Reef quartzite, but also some on sands (cut-off point < 20 g 100 g^{-1} B horizon clay) derived from the narrow Klapperkop quartzite bands running through the Timeball Hill shale. Examination of sites on Klapperkop quartzite revealed that, as in the case of diabase, tree growth did not appear to differ from that on the surrounding shales and thus seemed to have a closer affinity to Timeball Hill shale than to the spatially separated Black Reef quartzite, where growth is universally poor. Sites on Klapperkop quartzite were therefore allocated to shale after removal from the category *Quartzite*, which was then renamed *Black Reef*. With this adjustment best subsets regression once again returned the same subset as before, but with a further improvement in R^2.

The negative regression coefficients for the dummy variable categories resulted from the choice of the category with the largest mean *site index* as reference category (*Dolomite*). To eliminate the minus signs the reference category was switched to the smallest category (*Black Reef*).

The improvements to Model 2.1 described above led to a change in the regression coefficients for *geology* (Table 2.10).

Table 2.10 Regression coefficients for *geology* in the improved field model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Black Reef	0,000	(ref. cat.)			
Selati	3,403	1,24	0,23	2,74	0,00701
Timeball	4,697	1,10	0,54	4,25	0,00004
Oaktree	3,253	1,15	0,22	2,84	0,00525
Granite	7,335	1,23	0,81	5,95	<0,00001
Dolomite	6,282	1,12	0,66	5,61	<0,00001

Refining the *slope position-site index* relationship

As in the case of *geology*, regression coefficients for some *slope position* categories in Model 2.1 differed only slightly and require closer examination. The improvements to Model 2.1 described above, together with a switching of the reference category from the largest (*foot slope*) to the smallest (*wide crest*), led to changes in the coefficients shown below (Table 2.11).

From this table it now appears that the only category which was significantly better than *wide crest* (the poorest), was *foot slope* (the best). This suggests that there should only be two categories, viz. *foot slope* present, or absent. Consequently this combination of categories was tested. Although this exercise reduced the number of variables in the model, there was a drop in the R^2.

Table 2.11 Regression coefficients for *slope position* in the improved model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Wide crest	0,000	(ref. cat.)			
Narrow crest	0,123	0,84	0,01	0,15	0,88337
Upper slope	0,156	0,74	0,02	0,21	0,83250
Mid slope	1,116	0,68	0,13	1,65	0,10193
Lower slope	1,302	0,76	0,12	1,72	0,08857
Foot slope	4,336	0,95	0,30	4,58	0,00001

Returning to Table 2.11, however, it is noticeable from the coefficients that a different grouping is suggested. *Wide crest, narrow crest* and *upper slope* fall into a possible group, *mid slope* and *lower slope* into another, and *foot slope* remains a category in its own right. This grouping was tested and found to improve both significance and R^2. The new grouping for *slope position* was therefore substituted in the model, details of which are given in Table 2.12 (Model 2.2).

The Field Model

The improvements to Model 2.1 described above resulted in a new field model (Model 2.2), the coefficients of which are shown in Table 2.12.

Model fit

Model 2.2 appeared to fit the data reasonably well. As this model was only a tentative one, representing the first step in the process of model building, not a great deal of attention was paid to minor problems at this stage.

The regression diagnostics options of REGPAC (the detection of outliers and high leverage points) showed that there were no outliers. The plot of the residuals vs. predicted values revealed no trends in the data that might be indicative of a model misfit. The normal probability plot of the recursive residuals revealed no normality problems such as skewness or a light or heavy-tailed distribution. (Recursive residuals are a linear transformation of the ordinary residuals, such that they are identically and independently distributed (Galpin and Hawkins, 1984). They show the effect of successively deleting points from the data set, either forwards or backwards). Graphic plots using recursive residuals are available in REGPAC. If all the

Table 2.12 MODEL 2.2: Regression coefficients for the improved field model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Black Reef	0,000	(ref. cat.)			
Oaktree	3,280	1,13	0,23	2,91	0,00414
Selati	3,511	1,13	0,23	3,10	0,00231
Timeball	4,778	1,03	0,55	4,66	0,00001
Dolomite	6,340	1,05	0,67	6,02	<0,00001
Granite	7,418	1,15	0,82	6,54	<0,00001
Crest & upper slopes	0,000	(ref. cat.)			
Mid & lower slopes	1,077	0,41	0,13	2,62	0,00967
Foot slope	4,223	0,80	0,29	5,26	<0,00001
Altitude (centred)	-0,003	<0,01	-0,17	2,16	0,03260
Altitude ^{2} (cent.)	<-0,001	<0,01	-0,17	3,19	0,00173
Stoneline depth	1,528	0,62	0,16	2,48	0,01437
B.hor. thickness	0,011	<0,01	0,11	3,19	0,00173
Intercept	14,539	3,57			

R^2 = 0,6851 S.E. = 2,337

assumptions of normality are satisfied, then the normal probability plot of the recursive residuals should show a straight line through the origin. The plot will also reveal outliers.

2.5.1.4 Stand factors

It is possible that a proportion of the unexplained sum of squares could be attributed to "stand" factors such as stand density, seed source, etc. The Pearson correlation coefficient between *site index at 20 years* and *present stand density* was r = -0,12 and with *density at 20 years*, r = -0,13. These low correlations imply that the dependent variable, especially chosen to be as free as possible from this type of interference, was indeed influenced negligibly by stand density. It is, however, possible that thinning intensity, frequency and timing could have influenced *site index*. The poor records of thinning history back to 1932 precluded the use of any parameter expressing the combined effect of thinning. The possibility of an influence from seed source was remote (para. 2.3.3.).

2.5.2. SOIL ANALYTICAL VARIABLES

2.5.2.1 Preliminaries

Soil analytical variables used for model construction were those listed in Table 2.2. Correlation coefficients greater than 0,3 between these variables and *site index* are shown in Table 2.13.

Bearing in mind the problems associated with correlation coefficients already described in para. 2.5.1.1, some points of interest emerge from Table 2.13:

(i) Correlation coefficients for texture variables were lower than those for most other variables.

(ii) A horizon cations were better correlated with *site index* than B horizon cations.

(iii) *pH in* H_2O was more highly correlated with *site index* than was *pH in KCl*.

(iv) The highest correlation coefficient was that for *base status* (r = 0,57). For field- measurable variables it was *geology* (r = 0,66) (Table 2.6).

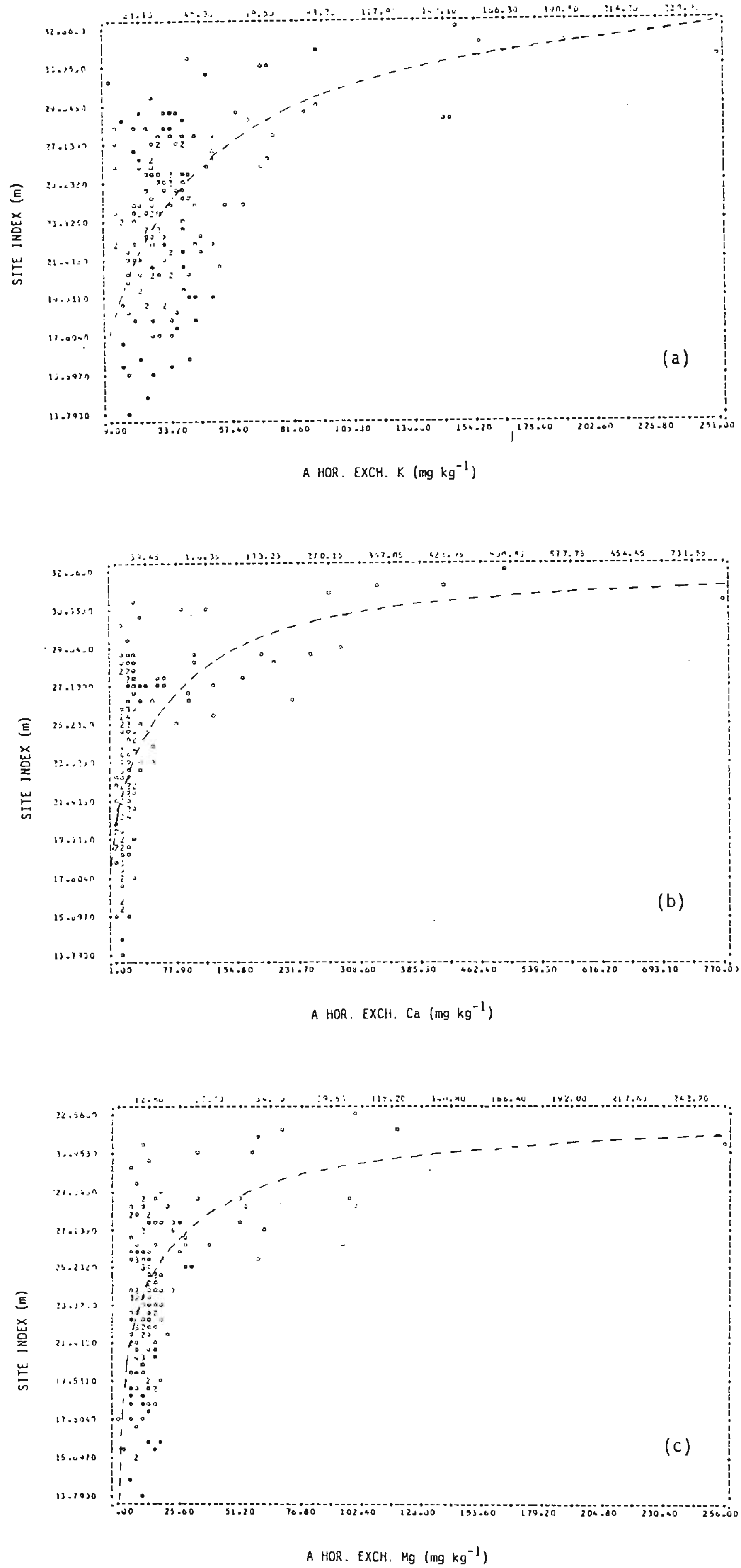
(v) The negative role of aluminium in nutrition is shown by the sign of the correlation coefficients for X_{73} and X_{99}, as is that of increasing acidity (X_{87}). The negative signs in the case of X_{55}, X_{62} and X_{84} cannot be explained at this stage.

Scatter diagrams were plotted to reveal outliers arising from possible errors, and to reveal non-linear trends. Strong logarithmic trends were apparent for *K*, *Ca* and *Mg* (Fig. 2.4 (a),(b) and (c)) as well as for sums of exchangeable bases. The shape of the curves in Fig. 2.4 makes it difficult to locate possible critical levels. Assuming that the critical level would lie near the point at which the curve begins to trend towards a straight line, the critical levels for A horizon soil cations would appear to be in the vicinity of 100 mg kg^{-1} for *K*, 200 mg kg^{-1} for *Ca* and 70 mg kg^{-1} for *Mg* (Fig. 2.4).

Table 2.13 Correlation coefficients (r) >0,30 between *site index* and soil analytical variables

No.	Variable	r
X_{55}	*Fine sand, A hor.*	-0,33
X_{58}	*Clay, B hor.*	0,34
X_{62}	*Fine sand, B hor.*	-0,30
X_{65}	*Bulk density, surface*	0,34
X_{67}	" " *, ratio*	0,34
X_{70}	*K, A hor.*	0,46
X_{71}	*Ca,* "	0,49
X_{72}	*Mg,* "	0,44
X_{73}	*Al,* "	-0,30
X_{75}	*K, B hor*	0,33
X_{76}	*Ca,* "	0,36
X_{77}	*Mg,* "	0,38
X_{84}	*Organic C, A hor.*	-0,36
X_{86}	*pH (H_2O), A hor.*	0,47
X_{87}	*Exch. acidity, A hor.*	-0,40
X_{89}	*pH (H_2O), B hor.*	0,40
X_{91}	*Exch. bases* (soil), A hor.	0,48
X_{92}	" " " *B hor.*	0,40
X_{93}	" " *clay, A hor.*	0,47
X_{97}	*Base status, A hor.*	0,57
X_{98}	" " *, B hor.*	0,40
X_{99}	*Aluminium saturation, A hor.*	-0,30

$P < 0,0001$ in all cases
$n = 159$



Figures 2.4 Scatter diagrams for *site index* on exchangeable *K* (a), *Ca* (b) and *Mg* (c). (Curves are free-hand approximations).

2.5.2.2 Regression analysis

Best-subsets regression was run on the data. Several runs were necessary to test substitutions in cases where variables were deleted for singularity reasons, e.g. inclusion of *total sand* with its components *coarse*, *medium* and *fine sand*. It was decided first to examine the role of those variables based on the sums of exchangeable bases (X_{91} to X_{100}) before that of the component variables. The following variables were selected by best-subsets regression for the model:

Coarse sand A horizon
Clay B horizon
pH (H_2O) B horizon
Base status, A horizon

R^2 0,4858

Although this appears to be a conveniently small subset with only four variables, *base status* actually comprises four component variables, each of which has to be analysed in the laboratory first. Replacement of *base status* with its component variables *exhangeable K*, *Ca*, *Mg* and *exchange acidity* resulted in an improvement in R^2 from 0,4858 to 0,5056. As the variable *exch. bases (soil)* also showed potential for inclusion in the model, a comparison was similarly run with its component variables *K*, *Ca* and *Mg*. In this case also, substitution of the component variables improved R^2 from 0,4615 to 0,4915. The next possibility for consideration was that the component elements of the variables based on sums of exchangeable bases might not all prove to be significant and that one or more might not be selected in subsequent regression runs. If this proved to be the case then fewer laboratory analyses would have to be done and the sums of exchangeable bases could be dropped. A full regression analysis was therefore run on the data with these variables excluded. This confirmed that sums of exchangeable bases were not necessary.

Residual plots confirmed the lognormal distribution indicated by the scatter diagrams, with lesser trends indicated for A horizon *coarse sand*, *P* and *Al*. Slight quadratic trends were indicated for B horizon *clay* and *coarse sand*. Transformations of these variables separately and in various combinations were tested in a succession of best-subsets regression runs and multiple regression analyses. The soil analytical variables which most accurately predicted *site index* of *P. patula* are shown in Table 2.14. (Model 2.3).

Table 2.14 MODEL 2.3: Regression coefficients for the soil analytical model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Ca, A hor. (log)	3,321	0,60	0,41	5,56	<0,00001
Clay, B hor.	0,116	0,02	0,38	6,31	<0,00001
Mg, B hor.	-0,090	0,03	-0,32	3,20	0,00166
K, B hor.	0,050	0,02	0,23	2,57	0,01124
pH (H_2O), B hor.	3,132	0,90	0,23	3,48	0,00065
Coarse sand, A hor.	0,102	0,03	0,22	3,92	0,00013
Al, A hor.	-0,643	0,28	-0,15	2,33	0,02112
Organic C, A hor.	-0,323	0,14	-0,15	2,32	0,02200
P, A hor.	0,126	0,06	0,12	2,05	0,04191
Intercept	-1,350	6,11			
R^2 = 0,6020	S.E. = 2,610				

The lowest eigenvalue was 0,17056, indicating no serious multicollinearity problems. Tests showed that there were no outliers. The normal probability plot of the recursive residuals showed that the normality assumption was valid.

Soil analytical variables were not as effective in predicting *site index* (R^2 = 0,6020) as field-measurable variables (R^2 = 0,6851). This has normally been the case in similar studies elsewhere, as reviewed by Hägglund (1981).

2.5.3 THE FULL MODEL

2.5.3.1 **Principal Components Analysis**

As described earlier, the problem of selection of a subset of variables for the full model was addressed by splitting the data into field-measurable and soil analytical variables, and selecting subsets by means of best-subsets regression.

Models 2.2 and 2.3 identified the key site factors with the greatest potential for inclusion in the full site model. At this stage it is opportune to determine whether a suitable subset could also have been selected had PCA been used instead. The procedure is fully described by Isebrands and Crow (1975). Briefly it involves choosing the coefficient or coefficients having the highest absolute value in each eigenvector, starting with the first eigenvector or principal component. The main advantage of the method lies in being able to select a subset of variables which are orthogonal. With highly multicollinear data, therefore, this would be the recommended method. PCA (SAS Institute, Inc., 1985) was run on the *P.patula* data.

The proportion of the total variation explained by the different components is shown in Table 2.15. The results were not very different from those obtained from the principal components analysis of the 439 sites (which included the *P.patula* sites) (Ch. 1, Table 1.17). There was little evidence of structure in the data, i.e. the variance was fairly evenly spread over a large number of components. In this case, therefore, there is little to be gained from using PCA to obtain orthogonality. PCA has, however, shown that the independent variables have been well chosen, each having some unique contribution to make to the overall variance. These results were also confirmed by factor analysis.

Table 2.15 Principal components analysis of *P.patula* site variables

Principal component	Eigenvalue	Difference	Proportion of variation (%)	Cumulative variation %
1	9,90	3,69	19,0	19,0
2	6,21	1,77	11,9	31,0
3	4,44	0,70	8,5	39,5
4	3,74	0,57	7,2	46,7
5	3,18	0,87	6,1	52,8
6	2,30	0,31	4,4	57,2
7	1,99	0,12	3,8	61,1
8	1,88	0,33	3,6	64,7
9	1,54	0,23	3,0	67,6
10	1,32	-	2,5	70,2

2.5.3.2 Preliminary models

The independent variables which appeared in the model derived from field-measurable site factors (Model 2.2) and the model derived from soil analytical site factors (Model 2.3), as well as other variables which were shown to have potential, were now combined in a regression analysis for the construction of a model to predict *site index* from all available site data. The model thus obtained as a first step, contained the variables shown in Table 2.16.

Table 2.16 MODEL 2.4: Preliminary regression coefficients for the full model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Black Reef	0,000	(reference category)			
Selati	2,703	1,11	0,18	2,45	0,01566
Oaktree	2,961	1,16	0,20	2,55	0,01179
Timeball	3,559	1,13	0,41	3,16	0,00192
Dolomite	4,552	1,12	0,48	4,08	0,00008
Granite	5,961	1,13	0,66	5,28	<0,00001
Ca, A hor. (log)	1,853	0,46	0,23	4,02	0,00010
Stone layer depth (log)	1,934	0,70	0,20	2,78	0,00621
pH, B hor.	2,223	0,87	0,16	2,56	0,01151
Altitude (cent)	-0,002	<0,01	-0,13	1,70	0,09067
Altitude $(cent)^2$	<-0,001	<0,01	-0,19	3,72	0,00029
Crest & upper slopes	0,000	(reference category)			
Mid & lower slopes	1,016	0,39	0,20	2,60	0,01018
Foot slope	2,609	0,77	0,18	3,37	0,00096
Vol. stones B hor.	0,019	0,01	0,11	1,71	0,08970
Thickness of B hor.	0,011	0,01	0,11	1,88	0,06231
Clay, B hor.	0,029	0,02	0,09	1,58	0,11546
Exch. acidity, B hor.	0,554	0,37	0,09	1,51	0,13312
Intercept	-0,510	5,53			

R^2 = 0,7533 S.E. = 2,105

The coefficient of determination of this model was higher than that of the model with field-measurable variables alone (R^2 = 0,6851; Model 2.2), or with soil analytical variables alone (R^2 = 0,6020; Model 2.3). However, this model had several problems:

(i) Some multicollinearity among the variables was indicated (lowest eigenvalue = 0,00395).

(ii) The regression coefficients for *altitude* were so low that rounding errors arising from cutting off the value of the coefficient at five decimal places could result in inaccurate estimates.

(iii) The variable *percentage of stones in the B horizon* apparently has the wrong sign. Due to decreased rooting space one would expect stony soils to influence *site index* negatively, as indicated by the sign of the correlation coefficient (r = -0,35).

(iv) The plot of the cumulative sums of the standardized recursive residuals against cusum number (Galpin and Hawkins, 1984) showed a significant departure from a random drift about the origin, indicating problems with the model such as the omission of an important variable or a change in variance of the model over the data.

(v) Several sites did not fit the model well. Although there were no outliers according to the tests performed by REGPAC, there were seven large residuals with deviations from the regression line of up to 5,3 m (Table 2.17).

(vi) Several variables had regression coefficients which were not significant (P = 0,05) (Table 2.16). Lack of statistical significance is not considered sufficient justification for omitting a term from the model (para. 2.5.2.3), but variables with high significance levels tend to inspire greater confidence in the model.

Table 2.17 Sites with large deviations in *site index* (S.I.) from the regression lines

Observation no.	Observed S.I. (m)	Predicted S.I. (m)	Residual (m)
123	28,17	22,89	5,28
122	31,42	26,68	4,74
125	27,94	23,63	4,31
103	14,51	19,35	-4,84
159	21,74	17,86	3,88
112	17,42	21,85	-4,43
59	30,38	26,02	4,36

The above model inadequacies were dealt with as follows:

Multicollinearity

Multicollinearity was reduced to an acceptable level (para. 2.5.4.3) through scaling the squared term of *altitude*. This was done by once again centring this variable (i.e. *altitude* centred, squared, centred). The problem of low coefficients for the two *altitude* variables was simply overcome by dividing *altitude* by 100 before centring. This had the effect of reducing the number of zeros of the coefficients.

Coefficient with the wrong sign

The apparent wrong sign of the coefficient for *vol. of stones in the B horizon* could be due to a number of causes (Montgomery and Peck, 1982 p 383):

(i) The range of the variable is too small.

(ii) Important variables have not been included in the model.

(iii) Multicollinearity is present.

(iv) Computational errors have been made.

In this case the problem is most likely to be due to multicollinearity. *Vol. of stones in the B horizon* was fairly closely correlated with *depth to stone layer* (r = -0,72), *Timeball shale* (r = 0,52) and *altitude* (r = 0,46). Interactions with these variables were therefore investigated. In the case of *depth to stone layer*, the transformation recommended by Carmean (1983) was:

depth x (100 - % of stone)

None of these interaction terms improved model fit or changed the sign of *vol. of stones in the B horizon*, however. Substitution with the next best variables removed the problem of the wrong sign, but greatly reduced the R^2. As *vol. of stones in the B horizon* is clearly an important variable, it was decided to retain it in the model, regardless of sign. A wrong sign creates uncertainty as to the role of the variable in prediction but does not affect the accuracy of the model as such (Galpin, 1981).

Cusum plots

The method of testing for significant departures from a random drift in the plot of the cumulative sums of the recursive residuals against cusum number is described by Galpin and Hawkins (1984). Having established that there was a significant departure from a random drift, the next step was to trace the source of the problem. This is possible if the data are in some natural order (Galpin, 1981). In this study the data were ordered on plot (site) number, which is not a natural sequence. As the model defect was most likely to be related to one of the variables, the data should be ordered (e.g. from maximum to minimum values) on each of the variables in turn until the problem is revealed. (This is a very time-consuming operation and it is a weakness of the REGPAC package that this operation has not yet been programmed).

The data set was ordered on the different variables in turn and cusum plots obtained. Variables such as *A horizon calcium* showed no significant departures from a random drift about the origin, but *geology* failed the test, indicating that there was a problem with this variable. The cusum plot (Appendix 8) showed that the problem lay among a group of sites on the Timeball shales, which fell significantly outside the random drift. The interpretation of the cusum plot is that several sites did not fit the *Timeball* shale category and that these should be investigated to determine why this was the case. The search involved the deletion of groups of sites with common properties thought to be a possible problem, and then obtaining fresh cusum plots to monitor the effect.

Firstly the sites with lowest *site index* were deleted, and then those with highest *site index*, but no improvement in the cusum plot resulted. Altogether 15 attempts were made. For example, it was noticed that among the group of sites with bad fit were some with exceptionally low rainfall (Morgenzon). As *rainfall* did not appear as an independent variable in the model in spite of having a high correlation with *site index*, it was thought that these sites might be influencing the cusum plot unduly. Deletion of these sites, however, decreased the R^2 and did not improve the cusum plot. Next the variable *rainfall* was forced back into the model, but the effect was similar. Another possibility was the subdivision of the category *Timeball* into *shale* and *diabase*. The first approximation of *geology* as a variable included a category *diabase*, but this was found to be an unnecessary subdivision (para. 2.5.1.3). However, this category of diabase included intrusions into all rock-types, whereas the possibility might exist that a separate category for diabase could well be justified in the case of *Timeball* only, as most intrusions occur in this formation. Consequently an additional category of *geology* to accommodate diabase intrusions in the Timeball Hill Formation was created and the regression analysis re-run. This resulted in a decrease in the R^2 with no improvement in the cusum plot, thus confirming the finding of para. 2.5.1.3 that diabase does not affect *site index* differently from the rock type into which it has intruded.

Simultaneously with this investigation into the cusum plot problem, the model improvements described in the section below were being made. It was found that as these improvements took place, there was a concomitant improvement in the cusum plot, until in the improved model (para. 2.5.3.3) the cusum plot was found to be completely satisfactory (Appendix 8). Although this exercise appears to have been a waste of time, nevertheless it was useful from the point of view of confirming that neither *rainfall* nor *diabase* need be included in the model.

Sites with poor model fit

In regression analysis it is common practice to either "make the best of a bad job" and retain badly fitting points in the model, or to regard them as outliers and delete them (Rayner, pers. comm). In this study, however, all data associated with these sites, including their soil profile descriptions, were carefully checked for possible reasons for poor model fit. In almost every case the problem was associated with the variable *depth to stone layer*, in that the measured *site index* appeared to be unlikely for the depth of stone layer recorded. These sites were then investigated in the field, adjustments made to the data where necessary and the regression line re-fitted. The sites with the poorest model fit were then identified once more and investigated in the field as before. This procedure was repeated altogether eight times until all the largest residuals for *depth to stone layer* had been fully investigated.

This process contributed greatly towards a clearer understanding and definition of *effective rooting depth*. Stone layers were confirmed as a major factor in the determination of this parameter. Earlier studies (para.

2.5.1.1) clearly indicated that stone layers with stones ≥ 40% by volume are critical. In the re-examination process it became apparent that the size of stones could also be an important factor. Grit and gravel-sized fragments, for example, were found to be non-restrictive. Stone layers proved to be critical only if they were unbroken and continuous over the entire area of the site under investigation. Degree of cementation or compaction is also an important factor, but was difficult to quantify. Further research on stone layers is therefore of great importance. When stone layers are not present, other restrictions such as the following have emerged as important in defining effective rooting depth: saprolite, a soft plinthic or other very wet horizon, a dense or compacted horizon, or any horizon above which there is a sudden and severe rooting restriction. The variable *effective rooting depth (ERD)* was now substituted for *depth to stone layer* in the model.

In the process of making these adjustments it was found that the reason for the poor model fit of some sites could not be ascertained. Some were located in an area known to have suffered from severe hail damage. In other cases faulty soil analyses or errors in planting dates (confirmed by ring counts) were suspected. The effect of deletion of these plots on both R^2 as well as on model validation was tested one at a time. The deletion of altogether seven plots was found to be necessary.

2.5.3.3 The improved model

The adjustment to the preliminary models described above resulted in an improved model (Model 2.5, Table 2.18). The adjustments described in para. 2.5.3.2 above have thus increased the R^2 from 0,7533 for Model 2.4 to 0,8632 for Model 2.5. There are fewer variables in the model and t-values for the coefficients are higher. The size of the largest residual has been reduced from 5,29 m to 2,91 m. Multicollinearity has been reduced to an acceptable level (lowest eigenvalue = 0,0412). The plot of the residuals versus predicted values shows that the regression assumptions are satisfied (Appendix 8). The normal probability plot of the recursive residuals shows that a normal distribution can be assumed (Appendix 8). The very slight deviation from a straight line indicates a tendency towards a light-tailed error distribution, which means that the regression is, if anything, conservative, so that the results will be more accurate than indicated (Galpin, 1981). As has already been shown, the cusum plots are satisfactory (Appendix 8).

Table 2.18 MODEL 2.5: Final regression coefficients for the full model

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Black Reef	0,000	(reference category)			
Selati	3,469	0,78	0,24	4,46	0,00002
Oaktree	3,758	0,79	0,27	4,79	<0,00001
Timeball	4,296	0,76	0,50	5,63	<0,00001
Dolomite	6,044	0,76	0,66	7,94	<0,00001
Granite	7,332	0,83	0,83	8,81	<0,00001
ERD (log)	5,119	0,46	0,53	11,16	<0,00001
Ca, A hor (log)	2,229	0,32	0,29	7,08	<0,00001
Vol. of stones, B hor.	0,046	0,01	0,28	6,03	<0,00001
Altitude /100 cent.	0,064	0,10	0,04	0,67	0,50729
(Alt /100 cent.)^2 cent.	-0,119	0,02	-0,23	5,92	<0,00001
Fine sand, A hor.	-0,045	0,02	-0,12	2,77	0,00634
Crest & upper slopes	0,000	(reference category)			
Mid & lower slopes	0,789	0,28	0,10	2,84	0,00515
Foot slope	2,003	0,56	0,14	3,56	0,00052
Intercept	6,045	1,20			

R^2 = 0,8632 S.E. = 1,516

2.5.3.3 Other potential variables

Before proceeding with the validation of the model it was necessary to test the substitution of other potential variables, this best being done at this stage of model development. These were bulk surface soil sample analyses, bulk density adjusted soil nutrient concentrations and other possible dependent variables.

Bulk surface sample analyses

In addition to soil chemical analysis results for the A 1 horizon from each soil pit, results were also available for a bulk surface sample to 15 cm depth taken from 20 points on diagonal lines across each site (para. 2.3.2). Direct comparison of pit sampling with bulk surface sampling was not possible as the sampling depths were not the same. A 1 horizons varied in thickness from 6 cm to 50 cm. The mean of 18,8 cm, however, was not far off the bulk surface sampling depth of 15 cm. Neither is it possible to compare fixed-depth sampling with A 1 horizon sampling as no fixed-depth samples were taken from the soil pits. Bearing in mind these problems a comparison is nevertheless of interest.

A regression analysis was therefore run with bulk surface analyses for *P*, *K*, *Ca*, *Mg* and *Al* replacing A 1 horizon analyses for these elements, and with the necessary transformations. As the surface of only 143 sites was sampled in bulk, a new model with A 1 horizon data based on 143 instead of 152 sites had to be constructed for comparison. Best-subsets regression selected the variables shown in Table 2.19.

Table 2.19 Variables in regression models for bulk surface analyses and A 1 horizon analyses (n = 143)

Bulk surface	A 1 horizon
Vol. of stones, B hor.	*Vol. of stones, B hor.*
Colour value, A hor.	*Geology*
Geology	*Slope position*
Slope position	*ERD* (log)
ERD (log)	*Altitude* (quadratic)
Altitude (quadratic)	*Fine sand, A 1 hor.*
Bulk surface P	*A 1 horizon Ca* (log)
Bulk surface Mg	
Bulk surface Al	
R^2 = 0,8685	R^2 = 0,8722

The bulk surface model had more variables and a lower R^2 than the A 1 horizon model. Bearing in mind the problems described above, the comparison indicates that bulk surface sampling is not necessarily superior to A 1 horizon sampling. It also confirms that plots were well located as the surface soils were uniform within plots.

Soil nutrients and bulk density

As there was considerable variation in *surface soil bulk densities* (334 kg m^{-3} to 1403 kg m^{-3}), it was thought likely that soil nutrients expressed on a mg kg^{-1} basis might not reflect their availability for tree growth correctly. A 1 horizon nutrient elements were therefore adjusted by multiplying with the correction factor *A 1 horizon thickness (mm)* x *A 1 horizon bulk density x 100*. A regression analysis was run with the density-adjusted nutrient elements replacing A 1 horizon nutrient elements in mg kg^{-1}, with log transformations where necessary. This model was then compared with one containing unadjusted nutrient elements, reduced to the 132 observations for which bulk densities were available. Best-subsets regression selected the variables shown in Table 2.20. It is evident that the two models do not differ greatly, but that the density-adjusted one has a slightly lower R^2 than the model with nutrients expressed in mg kg^{-1}. It would thus appear that the additional expense of expressing nutrients on a density basis is not justified.

Table 2.20 Variables in regression models for density- adjusted nutrients in mg kg^{-1} (A 1 horizon) (n = 132)

Density-adjusted nutrients	Nutrients in mg kg^{-1}
Vol. of stones, B hor.	*Vol. of stones, B hor.*
Colour chroma, A hor.	*Geology*
Geology	*Slope position*
Foot slope	*ERD* (log)
ERD (log)	*Fine sand, A hor.*
Fine sand, A hor.	*Ca, A hor.* (log)
Ca, density adjusted, *A hor.*(log)	
R^2 = 0,8108	R^2 = 0,8163

Choice of dependent variable

To investigate the possibility that expressions of tree growth other than the dependent variable used up to this stage might be more suitable, the independent variables of Model 2.5 were used to test different dependent variables (Cox, 1984). The dependent variables selected for comparison were those described in para. 2.4.3, viz:

$HT20_{10}$	Top height at 20 years based on the mean of 10 of the 30% largest D.B.H trees, defined as *site index*, the current dependent variable.
$HT20_5$	As above but based on the mean of the 5 largest trees.
$HT20_R$	As above but calculated from regression.
$HT20_{MAI}$	Mean annual height increment at 20 years with age at 3 m as the lower cut-off point.
$HT30_{10}$	Top height at 30 years.
$HT40_{10}$	Top height at 40 years.
$V20_{MAI}$	MAI20-index.

Total basal area.

Mean basal area.

Models for these dependent variables are compared in Table 2.21.

Table 2.21 R^2 values for models with different Y-variables using the same subset of X-variables.

	Y	R^2
Y_1	$HT20_{10}$	0,8632
Y_2	$HT20_5$	0,8440
Y_3	$HT20_R$	0,8216
Y_4	$HT20_{MAI}$	0,8036
Y_5	$HT30_{10}$	0,8576
Y_6	$HT40_{10}$	0,1409
Y_7	$V20_{MAI}$	0,6824
Y_8	Total basal area	0,3268
Y_9	Mean basal area	0,4176

Some important conclusions can be drawn from Table 2.21:

(i) Y_1 is confirmed as the most suitable measure of tree growth for site studies such as this.

(ii) The higher R^2 for Y_1 when compared with Y_2 demonstrates the importance of having a sufficient number of trees for determination of mean height.

(iii) Y_2 is equivalent to a 17% top height. Being closer to the more generally accepted 10% top height, one would have expected a higher R^2 than for a 30% top height, as the influence of stand density should be less. While this is not a strictly valid comparison as half the number of trees were used to calculate mean height in Y_2 (par. (ii) above), it does indicate that sensitivity to site influences has not been decreased by use of a 30% top height.

(iv) Height regression equations are normally used in site factor studies to derive top height at a fixed age. The lower R^2 for this method (Y_3) demonstrates the greater accuracy of the stem analysis method used in this study.

(v) The lower R^2 for Y_4 shows that the additional time required in its determination is not justified. This might not be the case, however, in second rotation stands subject to the greater influence of competing vegetation than in the first rotation. However, considerable difficulty was experienced in counting annual rings, and the method is not regarded as very accurate.

(vi) The small difference in R^2 between Y_1 and Y_5 shows that *top height at 30 years* was influenced largely by the same site factors as in the case of *top height at 20 years.*

(vii) The low R^2 for Y_6 indicates that height increment had culminated by this age and could no longer be used effectively to differentiate between sites.

(viii) The disappointing performance of Y_7 was probably due to its sensitivity to stand density. Insertion of *stems per hectare* on the right-hand side of the equation did not improve the R^2.

(ix) Y_8 (Meeuwig and Cooper, 1981) and Y_9 could probably only be used in fully-stocked stands of the same density.

2.5.3.4 **Validation of the model**

Twenty test plots were laid out on a wide variety of sites within the boundaries of the study area (Table 2.22). The stands sampled were mostly planted at a more recent date (average year 1954) than the stands sampled for model construction (average year 1939). The latter were also mostly first rotation stands, thus providing a good test for this and subsequent models.

Table 2.22 Description of test plots used for model validation

Plot no.	Location	Geology	Date planted	Measured *site index* (m)
175	Rosehaugh A34	Dolomite	1952/3	21,96
176	Spitskop C36	Oaktree	1941/2	22,13
177	Witwater D12	Granite	1952/3	27,52
178	Witwater D17	Granite	1954/5	30,47
179	Mac Mac B14	Dolomite	1954/5	25,47
180	Mac Mac C1	Dolomite	1953/4	24,85
181	Mariti D10	Granite	1954/5	25,95
182	Mariti A2	Granite	1948/9	25,88
183	Wilgeboom C2	Granite	1947/8	26,29
184	Morgenzon A29	Timeball	1949/50	21,04
185	Frankfort B16	Granite	1955/6	23,68
186	Brooklands C30a	Dolomite	1953/4	27,74
187	Brooklands F34b	Dolomite	1956/7	25,06
188	Brooklands F34a	Timeball	1955/6	24,89
189	Tweefontein A12	Dolomite	1962/3	25,76
190	Tweefontein A9	Dolomite	1960/1	26,08
191	Tweefontein A86	Oaktree	1957/8	25,17
192	Long Tom 13	Timeball	1955/6	24,72
193	Witklip B72	Granite	1956/7	28,03
194	Frankfort B17	Granite	1955/6	24,86

The same methods were used for recording dependent and independent variables as those used for the original plots. The range in *site index* for the validation plots was 21,04 - 30,47 (Table 2.22), while for the model plots it was 13,8 - 32,9 (Table 2.5). The validation plots therefore did not cover the poorest sites, but were representative of more average site conditions.

The measured and predicted *site index* ($HT20_{10}$) using Model 2.5 are compared in Table 2.23.

Table 2.23 Validation of Model 2.5 (full site model)

Plot no.	Measured *site index* (m)	Predicted *site index* (m)	Deviation (m)
175	21,96	21,68	-0,28
176	22,13	22,83	+0,70
177	27,52	25,48	-2,04
178	30,47	27,88	-2,59
179	25,47	25,80	+0,33
180	24,85	24,91	+0,06
181	25,95	25,15	-0,80
182	25,88	25,01	-0,87
183	26,29	24,82	-1,47
184	21,04	19,98	-1,06
185	23,68	23,41	-0,27
186	27,74	25,50	-2,24
187	25,06	25,24	+0,18
188	24,89	25,22	+0,33
189	25,76	24,32	-1,44
190	26,08	25,12	-0,96
191	25,17	24,46	-0,17
192	24,72	25,52	+0,80
193	28,03	26,64	-1,39
194	24,86	22,98	-1,88

Mean deviation = -0,75 m
Absolute mean deviation = 1,02 m
Absolute maximum deviation = 2,59 m

Model 2.5 predicts *site index* within a mean of 1,02 m, the absolute maximum deviation being 2,59 m. The model tends to underpredict *site index* by a mean of 0,75 m.

Although all the tests showed that multicollinearity was within acceptable limits (lowest eigenvalue = 0,04012; harmonic mean of the eigenvalues = 3,52; condition number of the correlation matrix = 84,99), nevertheless they are borderline, and one of the variables has the wrong sign. Ridge regression is advised by Hoerl, *et al* (1986) in the case of coefficients with the wrong sign. Consequently ridge regression was used to adjust the regression coefficients, using the Lawless and Wang ridge estimates (Galpin, 1981) (Table

2.24). Standard significance tests do not apply in the case of ridge regression and are therefore not shown. Although the R^2 of the ridge model (Model 2.6) is slightly lower than that of the least squares model (Model 2.5), the validation test (Table 2.25) shows that the ridge model is more accurate in prediction. Consequently Model 2.6 is accepted as the best full site model.

Table 2.24 MODEL 2.6: Ridge regression coefficients for the full site model, using the Lawless and Wang ordinary ridge estimates

X	Regress. coeff.	Stdd. coeff.
Black Reef	0,000 (ref. cat.)	
Selati	2,247	0,16
Oaktree	2,467	0,18
Timeball	2,946	0,34
Dolomite	4,590	0,50
Granite	5,712	0,64
ERD (log)	4,941	0,51
Ca, A hor. (log)	2,310	0,30
Vol. of stones, B hor.	0,043	0,26
Altitude /100, cent.	0,038	0,02
(*Altitude* /100, cent.)^2 cent.	-0,106	-0,21
Fine sand, A hor.	-0,055	-0,15
Crest & upper slopes	0,000 (ref. cat.)	
Mid & lower slopes	0,861	0,11
Foot slope	2,055	0,14
Intercept	7,910	
R^2 = 0,8588		

Table 2.25 Validation of the full site ridge model (Model 2.6)

Plot no	Measured *site index* (m)	Predicted *site index* (m)	Deviation (m)
175	21,96	21,46	-0,50
176	22,13	22,79	+0,66
177	27,52	25,22	-2,30
178	30,47	28,23	-2,24
179	25,47	25,76	+0,29
180	24,85	24,85	0
181	25,95	25,13	-0,82
182	25,88	25,06	-0,82
183	26,29	24,87	-1,42
184	21,04	19,80	-1,24
185	23,68	23,60	-0,08
186	27,74	25,55	-2,19
187	25,06	25,03	-0,03
188	24,89	25,27	+0,28
189	25,76	24,28	-1,48
190	26,08	25,10	-0,98
191	25,17	24,66	-0,51
192	24,72	25,34	+0,62
193	28,03	26,71	-1,32
194	24,86	23,08	-1,78

Mean deviation = -0,79 m
Absolute mean deviation = 0,98 m
Absolute maximum deviation = 2,30 m

2.5.4 OTHER POTENTIAL MODELS

2.5.4.1 **Geology models**

In many previous site factor studies the data were stratified according to geographical, altitudinal or soil parent material zones (Carmean, 1975; Graney, 1975; White, 1982 a). With the well-defined geological zones of the Escarpment area of the Eastern Transvaal, the possibility exists that a separate model for each of the major geological substrates might be more accurate than a single model with *geology* as a variable (Model 2.6). Models were therefore developed for the largest geological substrates on which there were a sufficient number of plots available, viz. *Granite* (n = 40), *Dolomite* (n = 42) and *Timeball Hill* (n = 45). Tables 2.26 to 2.28 show the regression coefficients for *Granite* (Model 2.7), *Dolomite* (Model 2.8) and *Timeball Hill* (Model 2.9). There were insufficient test plots available for each geology category for proper validation of the models.

Table 2.26 MODEL 2.7: Regression coefficients for *Granite*

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
ERD (log)	5,142	0,84	0,90	6,15	<0,00001
Vol. of stones, B hor.	0,066	0,02	0,59	3,97	0,00044
Altitude	0,006	<0,01	0,55	5,22	0,00001
Ca, A hor. (log)	2,114	0,45	0,55	4,66	0,00006
Crest	-2,249	0,51	-0,55	4,37	0,00014
Upper slope	-1,485	0,57	-0,38	2,61	0,01431
Mid slope	-2,052	0,52	-0,52	3,96	0,00045
Chroma, A hor.	-0,465	0,15	-0,31	3,15	0,00382
pH (H_2O), B hor.	-2,036	0,93	-0,27	2,20	0,03625
Coarse sand, A hor.	0,059	0,02	0,27	2,52	0,01756
Intercept	17,419	4,81			
R^2 = 0,7705		S.E. = 0,996			

Table 2.27 MODEL 2.8 Regression coefficients for *Dolomite*

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Ca, A hor (log)	3,762	0,53	0,63	7,12	<0,00001
ERD (log)	4,587	0,94	0,42	4,87	0,00002
Mid slope	2,149	0,58	0,26	3,70	0,00073
Vol. of stones, B hor.	0,045	0,02	0,21	2,71	0,01036
pH (H_2O), A hor.	2,335	0,97	0,21	2,41	0,02143
Value, B hor.	0,970	0,46	0,17	2,13	0,04062
Intercept	-4,663	5,34			
R^2 = 0,8418		S.E. = 1,602			

Table 2.28 MODEL 2.9: Regression coefficients for *Timeball Hill*

X	Regress coeff.	S.D.	Stdd. coeff.	t-value	Probability
ERD (log)	5,504	0,58	0,72	9,46	<0,00001
Altitude	-0,009	<0,01	-0,53	8,48	<0,00001
Vol. of stones, B hor.	0,044	0,01	0,33	4,48	0,00007
Thickness, A hor.	0,074	0,02	0,19	3,05	0,00430
Ca, A hor. (log)	1,669	0,69	0,15	2,43	0,02010
Upper slope	0,760	0,45	0,11	1,70	0,09800
Lower slope	1,389	0,65	0,14	2,14	0,03921
Value, B hor.	0,703	0,35	0,13	2,01	0,05220
Intercept	19,494	2,79			
R^2 = 0,8731		S.E. = 6,446			

2.5.4.2 The model with *geology* excluded

The construction of a model with *geology* excluded was attempted for several reasons. Firstly, by determining which site variables would replace *geology* in such a model, one might possibly gain more insight into the reasons why geology is so important for prediction of *site index* (highest standardized coefficients in Model 2.5). Secondly, much of the multicollinearity in Model 2.5 is probably due to correlations between *geology* categories and other variables. A more stable model might result if *geology* could be substituted with other variables. Thirdly, a model without *geology* might be applicable outside the study area where the geology is either at different altitudes than in the Sabie area, or is completely different.

Best-subsets regression analysis indicated that several models were possible, most of which contained many soil analytical variables. In view of the problems experienced in the accurate analysis of soil samples, it was decided to accept a subset with as few soil analytical variables as possible (Table 2.29), this being designated Model 2.10. Validation is shown in Table 2.30.

Table 2.29 MODEL 2.10: Regression coefficients for the model with *geology* excluded

X	Regress coeff.	S.D.	Stdd. coeff.	t-value	Probability
ERD (log)	5,434	0,52	0,57	10,45	<0,00001
Ca, A hor. (log)	2,777	0,34	0,36	8,26	<0,00001
Fine sand, A hor.	-0,095	0,02	-0,26	5,92	<0,00001
Vol. of stones, B hor.	0,030	0,01	0,18	3,49	0,00065
Altitude /100, cent.	-0,194	0,09	-0,12	2,28	0,02399
(Alt /100, cent)^2 cent.	-0,057	0,02	-0,11	2,88	0,00456
Crest & upper slopes	0,000	(reference category)			
Mid & lower slopes	0,596	0,31	0,08	1,91	0,05771
Foot slope	1,993	0,61	0,14	3,28	0,00132
Hue, B hor. 10YR	0,000	(reference category)			
Hue, B hor. 2,5 YR	0,934	0,30	0,12	3,07	0,00258
Hue, B hor. 7,5 YR	-0,385	0,46	-0,03	0,84	0,40463
Slope %	0,037	0,01	0,12	2,82	0,00556
Intercept	10,718	1,16			
R^2 = 0,8159		S.E. = 1,713			

Table 2.30 Validation of the model with *geology* excluded (Model 2.10)

Plot no.	Measured *site index* (m)	Predicted *site index* (m)	Deviation (m)
175	21,96	18,57	-3,39
176	22,13	23,35	+1,22
177	27,52	23,90	-3,62
178	30,47	26,33	-4,14
179	25,47	24,59	-0,88
180	24,85	23,86	-0,99
181	25,95	26,81	+0,86
182	25,88	24,94	-0,94
183	26,29	25,81	-0,48
184	21,04	19,07	-1,97
185	23,68	24,98	+1,30
186	27,74	24,99	-2,75
187	25,06	23,88	-1,18
188	24,89	24,49	-0,40
189	25,76	23,37	-2,39
190	26,08	24,56	-1,52
191	25,17	26,38	+1,21
192	24,72	25,61	+0,89
193	28,03	27,46	-0,57
194	24,86	24,26	-0,60

Mean deviation = -1,02 m
Absolute mean deviation = 1,57 m
Absolute maximum deviation = 4,14 m

2.5.4.3 The field model

In view of the delay, expense and uncertainty of soil analyses, a model comprising field-measurable variables only, would have advantages over the full model (Model 2.6), even if its accuracy were slightly less. However, some soil analytical parameters can either be reasonably well estimated in the field (e.g. *clay content*), or require very simple laboratory determinations (e.g. *pH*). Before excluding these variables therefore, various models containing *clay content* and *pH* either separately or in combination, were examined. They were then compared with models containing no soil analytical variables. Their inclusion was found to improve R^2 by 0,0029 (*B hor. clay*), 0,0007 (*A hor. pH*) and 0,0043 (both included), which is considered insufficient justification for their use.

A model with field-measurable site factors was developed during the preliminary stages of regression analysis (para. 2.5.1). As this was done prior to the model improvements described in para. 2.5.3.2 above, the R^2 was only 0,6615. Using the improved data set therefore, best-subsets regression analysis was again run with field-measurable independent variables only. Regression coefficients of the selected subset are shown in Table 2.31 and validation in Table 2.32.

Table 2.31 MODEL 2.11: Regression coefficients for the preliminary field model

X	Regress coeff.	S.D.	Stdd. coeff.	t-value	Probability
Black Reef	0,000	(ref. cat.)			
Oaktree	4,067	0,89	0,29	4,58	0,00001
Selati	4,139	0,90	0,29	4,60	0,00001
Timeball	5,611	0,81	0,66	6,92	<0,00001
Dolomite	7,730	0,82	0,84	9,38	<0,00001
Granite	9,125	0,89	1,03	10,21	<0,00001
ERD (log)	5,292	0,53	0,55	10,02	<0,00001
Vol. of stones, B hor.	0,046	0,01	0,28	5,12	<0,00001
Altitude /100 cent.	-0,072	0,11	-0,04	0,69	0,49430
(*Alt* /100, cent)^2 cent.	-0,132	0,02	-0,26	5,79	<0,00001
Crest & upper slopes	0,000	(ref. cat)			
Mid & lower slopes	0,739	0,32	0,09	2,32	0,02207
Foot slope	3,216	0,63	0,22	5,12	<0,00001
Intercept	6,201	1,29			
R^2 = 0,8092		S.E. = 1,777			

As in the case of Model 2.6, the variable *vol. of stones, B hor.* had a coefficient with the wrong sign. Again, substitutions were sought, but in all cases the alternative models had lower R^2's and were less accurate in validation than the model with *vol. of stones, B hor.* The necessity for including both the linear and quadratic terms for *altitude* was once again tested by dropping the linear term, but this decreased the R^2 and the efficiency of prediction when validated. Although all the tests showed that multicollinearity was within acceptable limits (lowest eigenvalue = 0,04823; harmonic mean of the eigenvalues = 3,38; condition number of the correlation matrix = 64,76), nevertheless the wrong sign of *vol. of stones, B hor.* is an indication of a small degree of multicollinearity. Consequently ridge regression was used to adjust the regression coefficients. (Table 2.33).

Table 2.32 Validation of the preliminary field model (Model 2.11)

Plot no.	Measured *site index* (m)	Predicted *site index* (m)	Deviation (m)
175	21,96	22,69	+0,73
176	22,13	22,49	+0,36
177	27,52	27,03	-0,49
178	30,47	30,77	+0,30
179	25,47	25,86	+0,39
180	24,85	25,23	+0,38
181	25,95	26,06	+0,11
182	25,88	25,93	+0,05
183	26,29	25,73	-0,56
184	21,04	20,23	-0,81
185	23,68	24,18	+0,50
186	27,74	27,19	-0,55
187	25,06	25,08	+0,02
188	24,89	25,09	+0,20
189	25,76	24,74	-1,02
190	26,08	26,93	+0,85
191	25,17	24,30	-0,87
192	24,72	24,37	-0,35
193	28,03	26,94	-1,09
194	24,86	24,80	-0,06

Mean deviation = -0,11
Absolute mean deviation = 0,54
Absolute maximum deviation = 1,09

Table 2.33 MODEL 2.12: Ridge regression coefficients for the field model, using the Lawless and Wang ordinary ridge estimates.

X	Regress. coeff.	Stdd. coeff.
Black Reef	0,000000	(ref. cat)
Oaktree	2,306599	0,17
Selati	2,410555	0,17
Timeball	3,865794	0,45
Dolomite	5,825321	0,63
Granite	7,035526	0,79
ERD (log)	5,032228	0,52
Vol. of stones, B hor.	0,041851	0,26
Altitude /100, cent.	-0,135666	-0,08
(*Alt* /100, cent)^2 cent.	-0,117914	-0,23
Crest & upper slopes	0,000000	(ref. cat)
Mid & lower slopes	0,803594	0,10
Foot slope	3,328019	0,23
Intercept	8,529655	
R^2 = 0,8005		

Both the Lawless and Wang ridge estimates and the Browne and Rock generalized ridge estimates (Galpin, 1981) were tested. As the former gave better predictions of *site index* of the validation plots, it is considered more appropriate. Although the R^2 of the ridge model (Model 2.12) is lower than that of the least squares model (Model 2.11), the validation test (Table 2.34) shows that this is the most accurate of the field models.

Table 2.34 Validation of the field model (Model 2.12)

Plot no.	Measured *site index* (m)	Predicted *site index* (m)	Deviation (m)
175	21,96	22,18	+0,22
176	22,13	22,40	+0,27
177	27,52	26,77	-0,75
178	30,47	30,54	+0,07
179	25,47	25,71	+0,24
180	24,85	25,11	+0,26
181	25,95	26,05	-0,10
182	25,88	25,97	+0,09
183	26,29	25,82	-0,47
184	21,04	20,13	-0,91
185	23,68	24,28	+0,60
186	27,74	27,43	-0,31
187	25,06	24,95	+0,11
188	24,89	25,01	+0,12
189	25,76	25,99	+0,23
190	26,08	26,07	-0,01
191	25,17	24,52	-0,65
192	24,72	24,11	-0,61
193	28,03	26,98	-1,05
194	24,86	24,99	+0,13

Mean deviation = -0,13 m
Absolute mean deviation = 0,36 m
Absolute maximum deviation = 1,05 m

2.5.5 CHOICE OF MODEL

From the aforegoing the following models have potential for the prediction of *site index* of *P.patula*:

1. Model 2.6: The full model
2. Model 2.7: The *Granite* model
3. Model 2.8: The *Dolomite* model
4. Model 2.9: The *Timeball Hill* model
5. Model 2.10: The model with *geology* excluded

6. Model 2.12: The field model

2.5.5.1 **Comparison of models**

The coefficients of determination, lowest eigenvalues and validation of the models are compared in Table 2.35.

Table 2.35 R^2 and validation comparisons of site models

Model no.	R^2	Lowest eigenvalue	Validation (m)		
			Mean deviation	Abs. Mean deviation	Abs. Max deviation
2.6	0,8588	0,04012	-0,79	0,98	2,30
2.7	0,7705	0,15555	-	-	-
2.8	0,8418	0,31265	-	-	-
2.9	0,8731	0,36988	-	-	
2.10	0,8159	0,27198	-0,02	1,57	4,14
2.12	0,8005	0,04823	-0,13	0,36	1,05

Model 2.6
The full model has a high R^2, but not the lowest absolute mean deviation from measured *site index* of the test plots. The value of 0,98 m for this parameter would be entirely acceptable in practice, but occasional errors of up to 2,3 m could be expected.

Models 2.7 to 2.9
Model 2.9 has the highest R^2 but model 2.7 has the lowest R^2 of all the models. Significance levels for all three models are lower than for Model 2.6. There were too few observations for the construction of models for *Selati*, *Oaktree* and *Black Reef*. Due to these problems, separate models for each geology substrate are not a satisfactory alternative to the model incorporating *geology* as a variable (Model 2.6). Nevertheless, these models could form a useful basis for extrapolation to other areas if more data were accumulated, e.g. the Timeball Hill Formation is extensive outside the study area. Comparing multicollinearity tests for Models 2.7 to 2.12 with Model 2.6, it is apparent that the deletion of *geology* as a variable from Model 2.6 has removed the source of a small degree of multicollinearity (Table 2.35).

Model 2.10
In spite of a relatively high R^2, the model with *geology* excluded has lower significance levels than Model 2.6. Model 2.10 does not predict *site index* of the test plots accurately enough for practical use. This confirms the importance of the variable *geology*. As in the case of Models 2.7 to 2.9, removal of *geology* in Model 2.10 reduced the small degree of multicollinearity present in Model 2.6.

Model 2.12
Although the R^2 of the field model is not as high as that of Models 2.6 and 2.10, the accuracy with which *site index* of the test plots is predicted leaves no doubt that this is the preferred model. With an absolute mean deviation of only 0,36 m and an absolute a maximum deviation of 1,05 m, Model 12 can be recommended for practical use. It also has the advantage over the full model that soil analyses are not necessary. A pocket calculator is all that is required to predict *site index*, once the site parameters in the model have been accurately recorded.

2.5.5.2 Discussion

A probable explanation for the high R^2 values for Models 2.6 and 2.10 yet their poor predictive ability in comparison with Model 2.12, is the problem of soil analysis. The soil analyses for the validation plots and those for the plots upon which the model is based were performed by different laboratories. Large variations in soil analysis results among different laboratories is a worldwide problem (Van den Burg, 1976) and could be the reason for the poor predictability of the full models. This makes the use of models 2.6 and 2.10 risky.

The question arises whether prediction of *site index* of the 20 test plots can be accepted as an adequate test. Although the validation plots do not represent the same extremes of *site index* as the plots on which the models were based, they do represent average conditions in the region, and a fair degree of confidence can be placed in the validation. It is indeed possible that some sites in the region will not be well predicted but they should be regarded as the exception rather than the rule. The 152 plots used for model construction can be regarded as a representative sample of site conditions within the study area. In areas of possible uncertainty, further test plots could be laid out relatively easily. Of interest is the accuracy of Model 2.12 in spite of the fact that the validation stands were planted during different rainfall cycle conditions from those of the stands used for model construction (this would tend to indicate that cyclical trends in rainfall are evened out over a 20-year growth period). The 152 plots used for model construction as well as the 20 plots used for validation were laid out in genetically unimproved stands. An adjustment equivalent to the expected genetic gain would have to be made for improved stands.

The model comparison has shown that important variables such as *geology* which are responsible for a small degree of multicollinearity in the models, should not for this reason be discarded (Model 2.12), but rather retained and the regression coefficients adjusted by ridge regression.

It is improbable that Model 2.12 could be further refined in its accuracy of prediction, although the R^2 value indicates that some 22% of the total variation in *site index* remains unaccounted for. This could be due to the omission of some unrecorded site parameter (e.g. *slope length* or some estimate of soil drainage), or to unquantifiable sources of variation such as errors in planting date, the effect of thinnings, pests, diseases, hail, drought and fire. Seed source has already been discussed in para. 2.3.3.1. What has been simply demonstrated is that the coefficient of determination alone is an inadequate guage of model potential, and that validation with independent data is essential.

The only other site factor study in *P.patula* to achieve equivalent coefficients of determination was that by Evans (1974), whose best model contained soil analytical variables and should be compared with Model 2.6. The R^2 was 0,84, compared with 0,86 for Model 2.6 (Table 2.36). All other known *P.patula* models were less successful. Comparison is, however, difficult without validation.

Table 2.36 Comparison of R^2 values for *P.patula* site models

R^2	Reference
0,86	This study, Model 2.6.
0,84	Evans, 1974.
0,53	Castaños, 1962.
0,48	Grey, 1978.
0,47	Hardcastle, 1976.
0,30	Schönau and Wilhelmij, 1980.

2.6 DISCUSSION: SITE RELATIONSHIPS

The models described above serve the dual purpose of *site index* prediction and identification of the key site variables related to tree growth. It is necessary to examine the role of the site variables thus identified as well as possible reasons for the exclusion of others from the models. Two important considerations should be borne in mind. Firstly, as previously stated, the site variables are not necessarily the cause of variation in *site index*, only that they are related in a strictly statistical sense. Secondly, it is difficult to determine the importance of the site variables independently of one another in multiple regression (Keenan and Candy, 1983) as they are seldom truly independent.

2.6.1 SOIL ANALYTICAL MODELS

2.6.1.1 Soil analytical variables related to tree growth (Model 2.3)

Exchangeable bases

Of the variables based on the sums of exchangeable bases, *base status* and *exchangeable K + Ca + Mg per kg soil* were important predictors of *site index*, but the component variables making up these groups proved more useful (para. 2.5.2.2). *A horizon log Ca*, *B horizon Mg* and *B horizon K* all appeared in the model, but *Ca* appeared to exert the strongest influence. In fact, *Ca* was the single most important variable in the model as it had the highest standardized regression coefficient (Table 2.14). Although Ca deficiency has not been widely reported in the literature as a key site factor limiting tree growth rate, there is increasing evidence that forest soils in southern Africa are deficient in this element. Ca was found to be the most limiting nutrient for *P. patula* in Swaziland (Evans, 1971), for black wattle (Schönau, 1969) and for *Eucalyptus grandis* in Natal (Herbert, pers. comm.).

The log transformation of *Ca* in Model 2.3 implies that the improvement in *site index* gradually decreases above a certain concentration of *Ca*. The scatter diagram (Fig. 2.4) showed this level of *Ca* to be in the vicinity of 200 mg kg^{-1}. When all the variables in Model 2.3 are held at their mean values and a progression of theoretical values is inserted for log *Ca*, a regression curve of *site index* on log *Ca* can be plotted (Fig. 2.5). Although this procedure is not strictly correct, due, amongst others, to the non-orthogonality of the variables, it is often used to indicate likely trends (Graney, 1975; Schmidt and Carmean, 1987). This "trend graph" is probably closer to the true relationship between *site index* and *Ca* than that portrayed by the scatter diagram, as the influence of the other variables in the model are accounted for. Fig. 2.5 confirms that the critical level for A horizon exchangeable *Ca* may lie in the vicinity of 200 mg kg^{-1}.

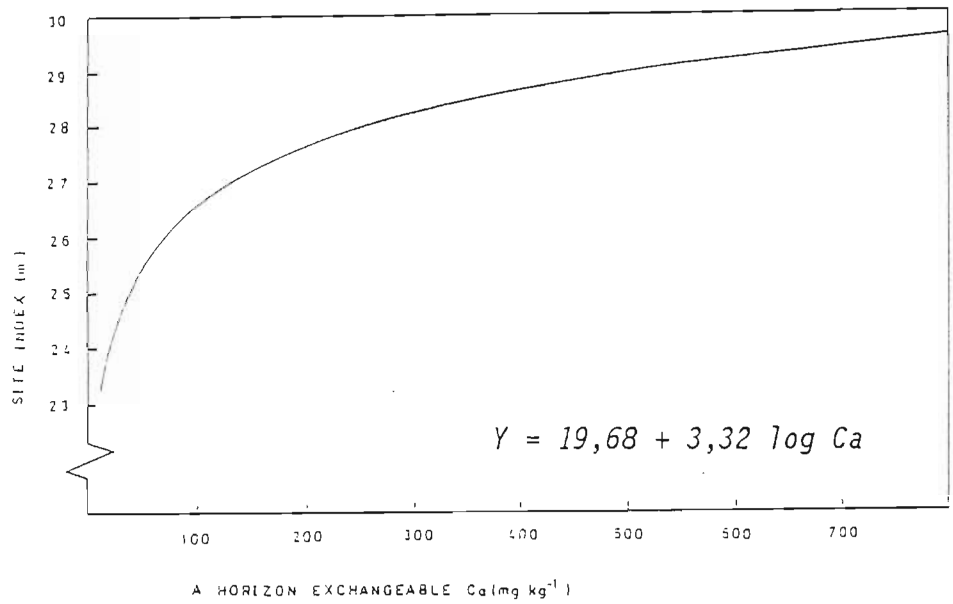


Figure 2.5 Trend graph of *site index* on log *exchangeable Ca* (other variables in model held at mean values).

K and *Mg* also appear in Model 2.3, but their role appears to be a lesser one (in a stastical sense) than that of *Ca*. Although the correlation coefficient for *Mg* was positive (Table 2.13), in the presence of the other variables in the model the regression coefficient becomes negative. This implies a possible oversupply of Mg. A closer examination, however, showed that *Mg* was correlated with two other variables in Model 2.3, viz. *K* (r = 0,78) and log *Ca* (r = 0,63). It is therefore possible that this apparent multicollinearity could have resulted in a wrong sign for the regression coefficient of *Mg* (para. 2.5.3.2). According to standard tests, however, these was no serious multicollinearity in Model 2.3 (para. 2.5.2.2). Whether the coefficient for *Mg* has the wrong sign or not, is therefore uncertain.

Available phosphorus

The t-value for the regression coefficient for *A horizon P* was only just significant, implying that it does not influence *site index* strongly. The correlation coefficient was less than r = 0,2. This is somewhat surprising in view of the low Bray 2 extractable P levels of the soils ($\bar{x}$ = 6 mg kg^{-1}, Table 2.2) and the generally good reaction to applied phosphates in most other species of pine in the southern hemisphere (Pritchett, 1979). However, in a similar study in Swaziland, Evans (1971) found that Bray 2 P was not related to *P.patula* site index. Another possible explanation for the minor role of *P* could be that although it may generally be deficient, its variation may be too small for it to have a strong relationship with *site index* as a predictor. Table 2.2, however, shows that the variation in *P* is, in fact, quite large. The implications could be that *P.patula* in the Eastern Transvaal is acquiring a considerable amount of its P from sources other than inorganic P and that the total amount of P so obtained is almost sufficient for its needs. In Swaziland Morris (1984) found that the supply of P to the biomass in *P.patula* involved quantities considerably in excess of those extracted by Bray 2, and concluded that the supply must have come from the mineralization of organic P. As the organic carbon content of Eastern Transvaal top soils is high ($\bar{x}$ = 4,0%, Table 2.3.3) this could indeed be the main source of P, and requires further research.

Organic carbon

In the light of the above comments concerning P, it is somewhat surprising that the regression coefficient for *A horizon organic carbon* was negative. One would have expected organic matter to be a seat of high nutrient levels, but in fact the correlation coefficients between *organic carbon* and all nutrients were low and negative. This is in contrast with the findings of other studies (Ralston, 1964; Row, 1960). A likely explanation, however, is that the negative role of *organic carbon* may be due to its association with soils which have a moist micro-climate. The poorest tree growth occurs on soils with high *organic carbon* levels (Black Reef and Oaktree substrates) due to their wetness. This conclusion is substantiated by the fact that *A horizon aluminium* is positively correlated with *A horizon organic carbon* (r = 0,42).

Exchangeable aluminium

The negative regression coefficient for *A horizon aluminium* confirms the depressive effect of exchangeable *Al* on tree growth. In low phosphate, acid soils, aluminium may affect nutrition by reducing uptake and/or translocation of P, and by restricting root-growth (Truman *et al*, 1983). The extent to which Al levels could have been affected by afforestation is not known.

pH

Soil acidity has sometimes been found to have an influence on tree growth (Pritchett, 1979). *B horizon pH* (H_2O) appears in Model 2.3 although the correlation coefficient for *A horizon pH* with *site index* was higher (Table 2.13). As the uptake of nutrients is promoted by higher pH, it clearly plays an important role. *pH in KCl* only appeared in models with large subsets and is evidently less important than *pH in water*. The eigenvalue test for multicollinearity (Model 2.3) showed that the variables in the model were not highly correlated. Thus any relationship between *pH* and *Ca* or *Al* is not likely to be strong.

Texture

Tree growth has in many instances been found to be related to soil texture (Pritchett, 1979). In this study the positive effect on *site index* of increasing *clay content* can be interpreted in that finer textured soils have a higher cation exchange capacity. Also in the specific case of the Eastern Transvaal, coarser textured soils are associated with Black Reef parent material, frequently poorly drained due to shallow bedrock. *Site index* of *P. patula* improves as the *coarse sand content* of the A horizon increases. The reasons for this are by no means clear, but a possible explanation is that coarse sandy soils may be better drained than soils with a high percentage of fine sand. A similar trend is reported for *Acacia mearnsii* on Hutton soils (Schönau, pers. comm.).

Density

It was somewhat surprising that none of the bulk density variables showed any potential for inclusion in the model, especially in the light of the findings in para. 2.5.3.2 that dense horizons influence *effective rooting depth*. The analysis problems described in Ch. 1 para. 1.5.1 may, however, have influenced the results.

2.6.1.2 General

A problem with soil properties which should be noted is that many of them, (e.g. nutrients, organic carbon, pH, bulk density), can be influenced by tree growth. This could complicate the search for site factors useful in predicting *site index* in that the extent of this influence cannot be easily quantified. Most of the sites studied were located in first rotation stands. Problems may become more apparent in subsequent rotations. Other problems associated with soil analyses which may influence results are the following:

(i) The need for samples to be taken in such a manner as to be representative of the whole site under investigation. The problems presented by soil variability have been reviewed by Beckett and Webster (1971). This would not, however, appear to have been a problem in this study (para. 2.5.3.3).

(ii) Accuracy control in the analytical process must be of a high standard.

(iii) Procedures to analyse "available" quantities of a nutrient may be applicable to certain crops but not to others.

(iv) The high cost of analyses.

2.6.2 FIELD MODELS

Most field-measurable variables which are components of these models act as surrogates for the factors which influence tree growth directly, such as temperature, soil climate and soil nutrients.

2.6.2.1 Site variables in Model 2.12 (the field model)

Geology

Geology has frequently been found to be a good indicator of site potential (Pritchett, 1979). Geology cannot influence site index *per se*, but is more likely to act as a surrogate for other variables which may do so more directly. In this study the importance of geological substrate as an integrator of site properties not accounted for by other variables in the model is shown by Fig. 2.6. Geological substrates such as diabase and Klapperkop quartzite have already been shown to have little influence on *site index* (para. 2.5.1.3) and are therefore not shown in Fig. 2.6. This bar chart indicates the relative importance of the different geological substrates once the effect of the other variables in the model have been accounted for by holding them at their mean values. Fig. 2.6 indicates that *geology* is responsible for differences in *site index* of up to 7 m, and is therefore an important variable. Boundaries are fairly easily located in the field (Ch. 1, para. 1.5.2) or by reference to the geology map (Fig. 1.3).

One of the objectives of developing a model with *geology* excluded was to determine which variables would replace *geology*, thereby possibly gaining insight into the reason for its importance (para. 2.5.4.2). Model 2.10 was chosen out of several possible models because it comprised the fewest soil analytical variables. The variables *Hue B hor.* and *slope* were the only ones to replace *geology*, but were the least important variables in the model (lowest standardized coefficients). They could therefore not be regarded as

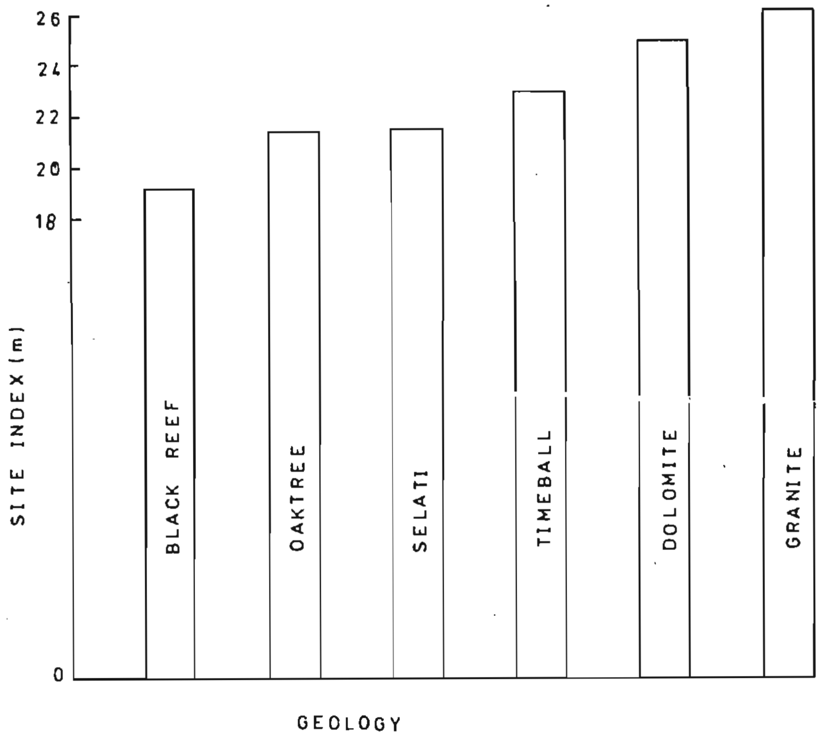


Figure 2.6 Trend graph of *site index* on *geology* (other variables in model held at mean values).

important differentiators between geological substrates.

The best alternative to Model 2.10, however, comprised many soil analytical variables. *A horizon fine sand*, *A horizon K*, *A horizon Mg* and *A horizon log Ca* were important variables while several others of low significance were also included. It may therefore be concluded that the importance of *geology* as a site factor could be due largely to soil nutrients. Drainage was not recorded as a variable but *A horizon fine sand* indicates that this could also be important. Of interest are the findings of Turvey *et al* (1986) that soil chemical parameters and sand content were predominant in discriminating between geological groups in New South Wales. The influence of geology on soil properties has already been discussed Chapter 1.

Effective rooting depth

The relationship between *site index* and *effective rooting depth* for the major geological substrates is shown in Fig. 2.7. *Site index* decreases rapidly on soils with *ERD* shallower than approximately 50 cm (In natural stands in Mexico, *P.patula* is replaced by other species on shallow soils (Castaños, 1962)). On deeper soils there is a gradual increase in *site index* until the maximum *ERD* of 150 cm reached. From the slope of the curves in Fig. 2.7,

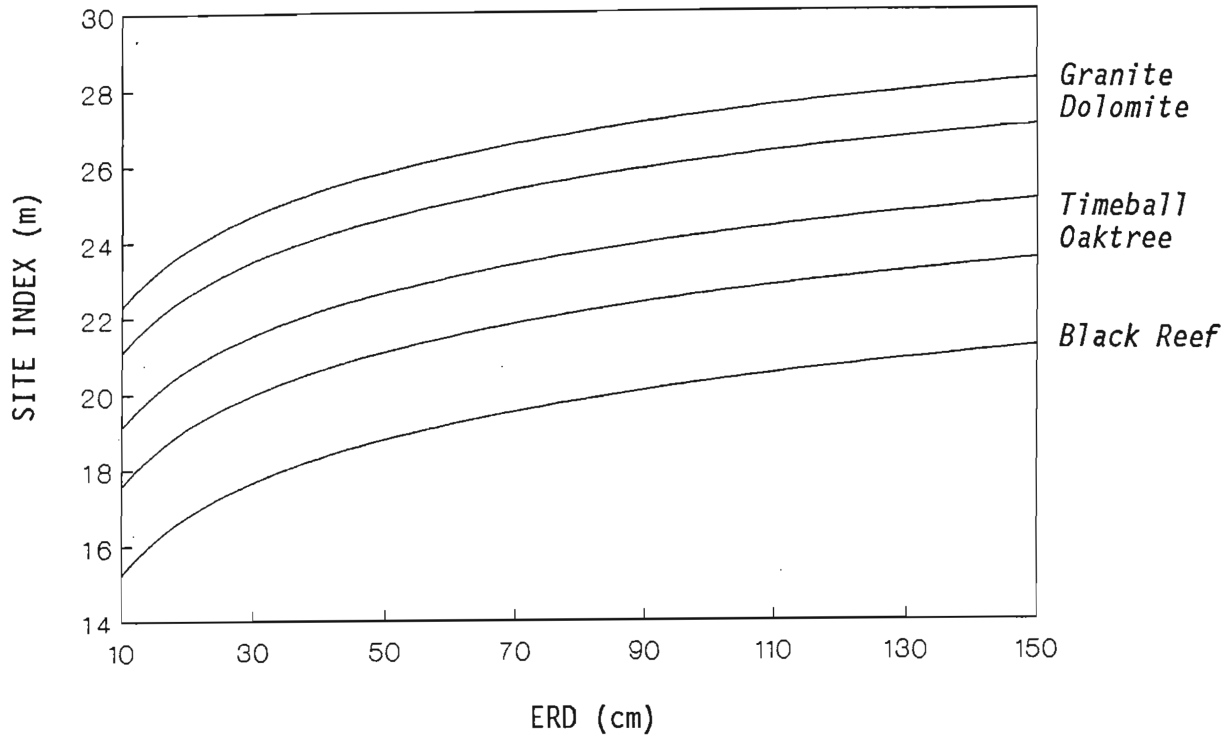


Figure 2.7 Trend graph of *site index* on *log ERD* and *geology* (other variables in model held at mean values). *Selati* is not shown as it nearly coincides with *Oaktree*. The equations are:

Granite	:	Y = 17,26 + 5,03 log *ERD*
Dolomite	:	Y = 16,05 + 5,03 log *ERD*
Timeball	:	Y = 14,09 + 5,03 log *ERD*
Oaktree	:	Y = 12,53 + 5,03 log *ERD*
Black Reef	:	Y = 10,22 + 5,03 log *ERD*

however, it is apparent that a further increase in *site index* could be expected on soils deeper than 150 cm. As many as 30% of the plots were on soils deeper than 150 cm. As *ERD* was assessed to a maximum of 150 cm, the model can therefore be expected to underpredict *site index* by a small but unknown amount when *ERD* is deeper.

One or other expression of soil depth has been found to strongly influence tree growth in most studies reported in the literature (Carmean, 1975); Pritchett, 1979; Ralston, 1964), and this study is clearly no exception. What is somewhat surprising, however, is that soil depth did not appear in any of the *P. patula* models of Evans (1971), Grey (1978), Hardcastle (1976) or Schönau and Wilhelmij (1980), but only in the model of Castaños (1962). This may have been due to a possible failure to identify potential restrictions in the soil profile when assessing soil depth.

Although soil depth is usually defined as "depth to a restriction" (Geyer *et al*, 1980; Jackson and Gifford, 1974; Turvey *et al*, 1986), the term "restriction" has in turn seldom been defined in forestry on the grounds of scientific evidence. An exception is the study of Vincent (1986), in which several different soil depth parameters were tested in discriminant models. In seeking to identify restrictions for the purpose of defining *effective rooting depth* in the study area of the Eastern Transvaal, 20 different parameters expressing soil depth (Table 2.2) were tested in regression analyses.

Of these parameters, *depth to ≥ 40% stones* has emerged as that which was most closely related to *site index* of *P.patula*. Size of the coarse fragments was important in that grit layers had little influence (para. 2.5.3.2). Nearly 50% of the soils surveyed had stone layers of at least 40% stone, and these occurred mostly within 50 cm of the surface. Stone layers tend to restrict surface feeding roots (Fig 2.8).

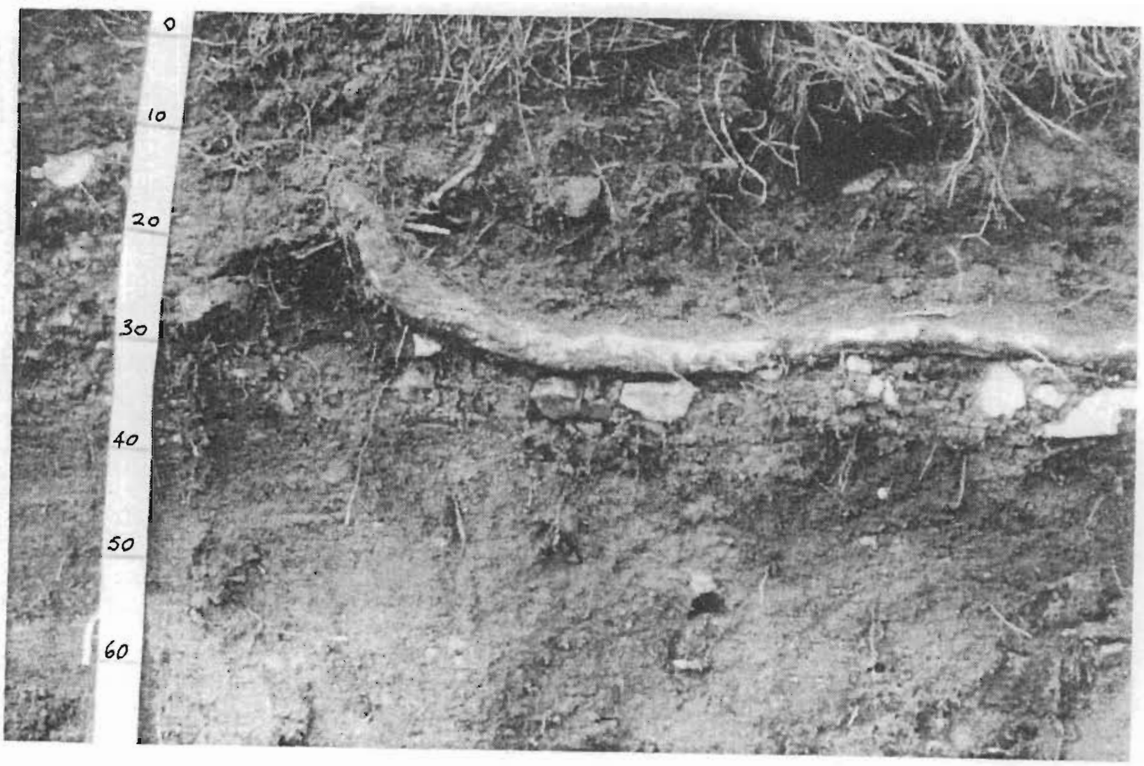


Figure 2.8 Surface root of *P. patula* deflected by a 50% stone layer of quartz in the A 3 horizon of a Hutton soil form on granite substrate (Frankfort S.F.)

It was noted that stone layers act as an effective barrier to the upward movement of moisture during the dry season, the surface soil having been dried out by evapotranspiration. There are two possible explanations for their effect on tree growth:

(i) A temporary soil water deficit may be caused at the beginning of the growing season. The degree to which water uptake is restricted is not clear, however, as tap and sinker roots were frequently observed to have penetrated stone layers.

(ii) A more likely explanation is that the temporary soil water deficit restricts the uptake of nutrients by the surface feeding roots.

During the process of investigation of large residuals in fitting a regression line to the data (para. 2.5.3.2) it became apparent that saprolite, dense horizons and wet horizons acted as restrictions when stone layers were not present. While saprolite was normally identifiable without much difficulty (bleached matrix, recognizable lithology or geogenic colouring), dense and wet horizons required greater subjectivity in their assessment. Any horizon markedly denser or more compacted relative to the horizons above it qualified for classification as a restriction. The presence of such a restriction was usually indicated by a noticeable concentration of roots above it. It was important to distinguish between a dense horizon and one which was hard only in dry soil. Similarly, in soils classified as wet in the study area (Griffin, Avalon and Longlands forms), there was normally a marked concentration of roots above the wettest horizon, indicating a restriction and confirming the aversion of *P. patula* to wet soils. Apart from these two instances, *depth of rooting* (X_{22}, X_{23}) was not a good indicator of *ERD*. The single most important restriction in determining *ERD*, however, was *depth to ≥ 40% stones*. A regression analysis of all soil depth parameters showed that *depth to ≥ 40% stones* accounted for 93% of the variation in *ERD*.

For *P. patula* in the study area *effective rooting depth* may thus be defined as depth to at least 40% stones by volume, to saprolite, to a dense horizon or to a wet horizon, whichever occurs closest to the surface. Further research is, however, necessary to remove the subjectivity associated with some of the assessments. It should be noted that *ERD* will be different for different species, depending largely on how demanding in its site requirements a particular tree species may be.

Volume of stones in B horizon

The problem of the wrong sign of the regression coefficient for this variable has already been discussed (para. 2.5.3.2). By reducing root space and water holding capacity, subsoil stoniness has been found to influence tree growth negatively (Geyer *et al*, 1980; Graney and Ferguson, 1971; Mogren and Dolph, 1972). However, White (1982) found the opposite. Increasing stone content improved the growth of Scots pine by improving drainage. Under the high rainfall conditions of the Escarpment area and with the aversion of *P.patula* to wet soil, (as indicated by this study) it is indeed possible that stoniness could improve drainage. Pritchett (1979) also points out that moderate amounts of coarse fragments may favour moisture penetration to deeper levels but that increasing stoniness reduces soil volume. If this were the case, however, one would expect the relationship to be curvilinear, which it is not. Furthermore, as the Pearson correlation coefficient for *volume of stones* is negative, it seems unlikely that the true relationship could be a positive one. One must therefore conclude that the sign of the regression coefficient is incorrect as a result of multicollinearity. In this case the true relationship cannot be determined, but the variable nevertheless remains an important one in the model.

Altitude

Altitude was responsible for differences in *site index* of up to 6 m (Fig. 2.9) The curvilinear trend was confirmed by the geology models (Models 2.7 to 2.9). In the *Granite* Model the regression coefficient for *altitude* was positive (Table 2.26). In the *Dolomite* Model, which applied to the middle of the altitude range, it did not influence *site index* (Table 2.27), while in the *Timeball* Model it was negative (Table 2.28). The most favourable altitude for *P.patula* in the Escarpment area evidently lies between 1200 and 1500 m, with the optimum at 1350 m (Fig. 2.9).

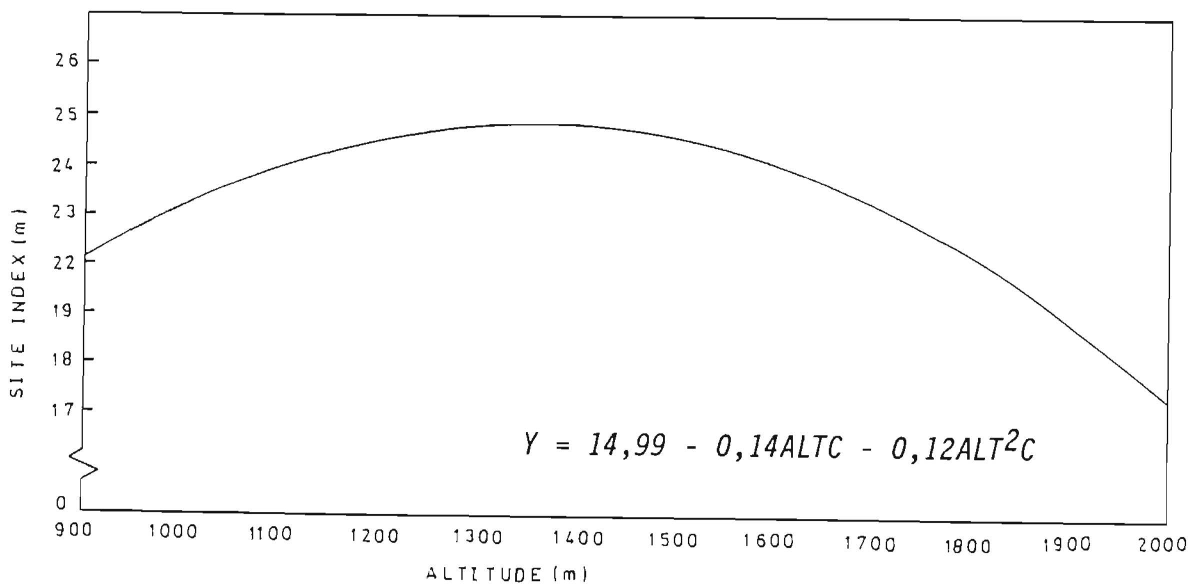


Figure 2.9 Trend graph of *site index* on *altitude* (other variables in model held at mean values).
(*ALTC* = *Altitude* centred. $ALTC^2C$ = *ALTC* squared, centred).

Site index is more severely affected by high altitude than low altitude, which is thought to be due to temperature.

Evans (1971) also found that the altitude relationship was curvilinear in Swaziland, with the optimum at 1250 m. That the optimum is lower than in the Sabie area may be due to the higher latitude of Swaziland. However, this may not be accurate as Evans derived the relationship from the scatter diagram and not the multiple regression relationship. In contrast with this study, top height of *P.patula* in Swaziland declined more sharply at low than at high altitude, which was considered to be largely a rainfall effect (Evans, 1971). Grey (1978) found that altitude was negatively correlated with *P.patula* site index in the Transkei, and that the relationship was linear. In the higher altitudes of Mexico, Castaños (1962) found that natural stands of *P.patula* declined in site index above 2400 m.

The mean value for centring *altitude / 100* was 13,82 and that for centring the squared term 5,60. Validation tests confirmed that the linear term should be retained.

Slope position

Slope position has been found to be important in many studies (Carmean, 1975; Ralston, 1964), including *P.patula* (Grey, 1978; Hardcastle, 1976). In this study *slope position* was responsible for differences in *site index* of up to nearly 4 m. (Fig. 2.10).

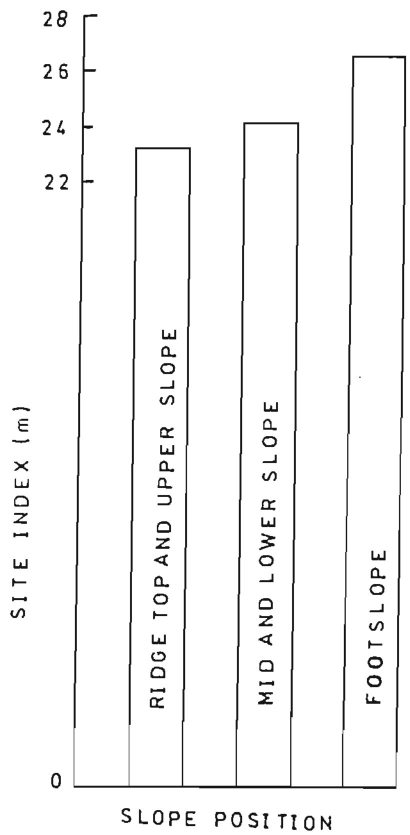


Figure 2.10. Trend graph of *site index* on *slope position* (other variables in model held at mean values).

There was a difference of 2,48 m in site index between the lower and footslope positions. The consequences of an error in assessment could therefore be serious, and care should be taken in determining the exact slope position. Unfortunately this is not always easy, and can sometimes be subjective. It is best done by aerial photography and use of a stereoscope. A further subdivision of the slope position between *lower slope* and *footslope* would reduce the chances of error, and further research is justified.

A parameter similar to *slope position*, viz. *percentage distance from ridge top to valley bottom*, was found to influence height growth of *P.patula* in Swaziland (Evans, 1971) and in the Transkei (Grey, 1978).

As in the case of *geology*, *slope position* is an integrator of site properties not accounted for by other variables in the model. These are thought to include slope and soil drainage, wetness and nutrients. The regression coefficients for *slope position* are larger in Model 2.12 (Table 2.33) than in the Model 2.6 (Table 2.24), indicating that in Model 2.12 *slope position* partially expresses the effect of the omitted variable *A horizon calcium*.

One would have expected a strong relationship between *slope position* and *soil depth*, but in fact the correlation coefficients were low (0,11 for *mid/lower slope*, 0,21 *foot slope*). Any such relationship would probably have been masked by the fact that *soil depth* was only recorded down to 150 cm whereas 30% of the plots were on soils deeper than 150 cm.

2.6.2.2 Site variables in other models

Although Model 2.12 is rated as the "best" out of several possibilities, the variables in the model are not the only ones to have important relationships with tree growth. Several site variables appeared repeatedly in the best of many models that were examined.

Colour *value* and *chroma* of the A horizon appeared frequently in good models, usually as alternates for *volume of stones*, *B horizon*. The positive coefficient for *value* and the negative one for *chroma* are difficult to interpret. *Hue of the B horizon* was an important variable in Model 2.10 and many others. The negative relationship with increasing yellowness of the subsoil further confirms the aversion of *P.patula* to wet soil conditions.

The only other variables to appear in good models were *slope %* and *summer*

summer *radiation index*. Soils are shallower and drier on steeper slopes. A logarithmic transformation of *summer radiation index* proved necessary. The positive relationship implies that tree growth is slightly better on gentle slopes with N,NE, NW and S aspects than on E, W, SE and SW aspects. However, the steeper the slope the poorer the growth on N aspect and the better the growth on S aspect. Significance levels for this variable were always low and it must be concluded that the relationship was not a strong one.

2.6.2.3 Site variables with minor roles

Rainfall

Although *rainfall* was correlated with site index (r = -0,48), it rarely appeared in models as a variable. Its influence is apparently better explained by other factors. The inverse relationship with *site index* is nevertheless of interest, implying that in some parts of the study area the rainfall is too high for *P.patula*. It can be assumed that a high rainfall regime would affect the soil climate by reducing aeration, increasing acidity and decreasing nutrient levels. That this is indeed the case is borne out by the fact that *rainfall* was negatively correlated with all *A horizon cations*, *P* and *pH*, and positively correlated with *A horizon Al*, *exchange acidity* and *organic carbon*. The correlation coefficients were not high, but were very highly significant.

Aspect

Aspect, its transformation (sine, cosine) and its interaction with *slope* (para. 2.5.1.1), were poor predictors of *site index*. Only when combined in an *index of summer radiation* did *aspect* exert a slight influence (para 2.6.2.2). That aspect plays no role in influencing *site index* of *P.patula* in the Eastern Transvaal comes as no surprise as it is in agreement with the work of both Evans (1971) in Swaziland and Grey (1978) in Transkei. Hardcastle (1976) found that aspect significantly affected the growth of *P.patula* in Malawi only in areas of low rainfall. It can be concluded that for the growth of *P.patula* in normal forestry regions in southern Africa *aspect* has little influence on *site index*. The influence of aspect on establishment (survival), however, is a different matter and beyond the scope of this study.

2.6.3 FULL MODELS

The fact that only two of the soil analytical variables from Model 2.3 appear in the "best" full model (Model 2.6), can probably be ascribed to their role being better expressed by the surrogates *geology* and *slope position.* When *geology* was removed from the model, several soil analytical variables were substituted (para. 2.6.2.1).

Calcium

The inclusion of *calcium* in addition to *geology* in Model 2.6 confirms that variation in soil levels of this element has important consequences for the growth of *P.patula*. In Swaziland Ca was found to be important in the *P.patula* nutrient cycle (Morris, 1986), and natural stands in Mexico are well supplied with this element (Castaños, 1962). The role of Ca has already been discussed in para. 2.6.1.

Texture

Of the soil texture variables, *fine sand content of the A horizon* appeared in Model 2.6 and many other models, as a negative relationship. Surface soils high in fine sand tend to be associated with wet sites (Selati, Black Reef and Oaktree substrates) and may be prone to compaction.

Soil classification

Some soil forms of the S.A. binomial soil classification system (Mac Vicar *et al*, 1977) are helpful in indicating conditions such as shallow depth (Mispah, Glenrosa), poor drainage (Katspruit, Kroonstad), or wetness (Griffin), but these forms are not common (Ch. 1). Nearly 60% of the 439 sites examined are of the Hutton form. As the entire range of *site index* (13,79 - 32,86 m) is to be found on Hutton soils, differentiation is not possible. The majority of soil forms found in the study area are differentiated at series level on the basis of S-value and clay content. As 99% of the soils are dystrophic, and *clay content* appears as a variable in few models, series is not likely to be a good predictor of *site index*. Soil classification thus has limited application in the prediction of *site index* in the Eastern Transvaal Escarpment area.

2.7 CONCLUSIONS

2.7.1 SURVEY TECHNIQUES

1. A minimum of ten trees per plot is advisable for calculation of mean *top height* in site studies such as this.

2. The method of stem analysis used to determine tree height at a fixed age was more successful than more commonly used regression methods.

3. Fixed-depth, bulk surface soil samples are not necessarily superior to A 1 horizon samples from a single soil pit in well-chosen, uniform sites.

4. Expression of soil nutrient availability adjusted for bulk density proved unnecessary.

2.7.2 REGRESSION METHODS

1. A common sense, practical approach from step to step in the model building procedure is essential, and was justified by the results obtained.

2. The use of dummy variables was shown to be an efficient method of expressing the influence of qualitative variables in multiple regression analysis.

3. For quadratic transformation of an independent variable it is necessary to include both the linear and the quadratic terms in the model.

4. Outliers and points which fit the model poorly should be fully investigated in the field and the model adjusted as often as necessary.

5. Principal components and factor analysis showed that there was little structure among the independent variables, confirming that the variables were well-chosen.

6. Ridge regression proved useful for adjusting the final coefficients, when slight multicollinearity problems were present.

2.7.3 SITE MODELS

1. Key site variables related to *site index* of *P.patula* were identified and satisfactorily modelled.

2. The coefficient of determination for the full model (Model 2.6) was higher than that attained for *P.patula* in other studies.

3. The coefficient of determination is a test of how well the regression line fits the data, but is not necessarily an indication of how well the model performs in practice. Validation was found to be an essential test of the accuracy of prediction of the model. No previous *P.patula* site models were ever validated.

4. In a comparison of nine possible dependent variables, *top height at 20 years* based on the mean of 10 of the 30% largest D.B.H. trees, defined as *site index*, was the expression of tree growth most accurately predicted.

5. *Top height at 30 years* could be predicted with almost the same accuracy, and using the same site variables, as *top height at 20 years*.

6. *MAI20 Index* could not be well predicted from site variables due to the confounding effect of thinnings.

7. Separate models for each of the geological substrates were not as accurate or as useful as a single model including all geological categories.

8. The fact that the most accurate model was one without soil analytical variables is ascribed to the problem of laboratory standards.

9. The regression coefficient of *vol. of stones B horizon* appeared to have the wrong sign in all models. Substitutions for this variable proved less efficient. The predictive ability of models was not affected by the wrong sign, but was improved by ridge regression.

10. The Field Model (Model 2.12) predicted *site index* of *P.patula* satisfactorily. The absolute mean deviation when tested on 20 validation plots was 0,36 m, with an absolute maximum deviation of 1,05 m.

2.7.4 SITE FACTORS RELATED TO SITE INDEX

1. Key site factors related to the growth of *P.patula* in the Escarpment area include *geology*, *effective soil depth*, *volume of stones in the B horizon*, *altitude*, *slope position*, *A horizon calcium*, *A horizon fine sand content*, *A horizon colour value* and *chroma*, *hue of the B horizon*, *slope gradient* and *summer radiation index*. Within the study area *rainfall*, *aspect* and *clay content* appear to play only a minor role.

2. Calcium appears to be the most deficient nutrient, and its variation affects *site index* more than do other soil nutrients. *Ca* did not appear to be strongly related to *pH*.

3. Individual soil nutrients were more efficient than variables based on sums of exchangeable bases in models to predict *site index*.

4. Critical levels for A horizon cations were approximately 200 mg kg^{-1} for *Ca*, 100 mg kg^{-1} for *K* and 70 mg kg^{-1} for *Mg*.

5. Bray-2 extractable P had little influence on *site index*, and *P.patula* is thought to obtain its needs on these soils from the organic P fraction.

6. Soil *pH in water* was more closely related to *site index* than was *pH in KCl*.

7. *Geology* has a strong relationship with *site index*, probably as a surrogate variable for soil nutrients and drainage. *Site index* is poorest on *Black Reef* and best on *Granite*.

8. The expression of soil depth most closely related to site index was *depth to at least 40% stones by volume*, to saprolite, to a dense horizon or to a wet horizon, whichever occurs closest to the surface. This is the most appropriate definition of *effective rooting depth* for *P.patula* in the study area.

9. Colluvial stone layers play an important role in determining *effective rooting depth*.

10. The optimum altitudinal range for *P.patula* is between 1200 and 1500 m. *Site index* decreases more rapidly at higher than at lower altitude.

2.7.5 FURTHER RESEARCH

1. Some of the models, particularly Model 2.9 (Timeball Hill) have potential for use outside the study area, and they should be tested with this end in view.

2. Research on the sources of P utilized by *P.patula* is required. Confirmation of the Ca deficiency indicated by the models is necessary. There is also uncertainty surrounding the role of Mg, i.e. whether it is generally deficient, or in oversupply.

3. Less subjective methods are still required to identify restrictions in the determination of *effective rooting depth*. The interaction between depth to stone layer and both the induration and thickness of stone layers should be studied. Suitable parameters to express drainage and the degree of wetness of a soil horizon are necessary.

4. Catena studies of changes in soil properties over slope profiles would help to reduce some of the subjectivity in the determination of *slope position*.

5. Due to the limitations of the computer package used, it was necessary to split the independent variables into two subsets for regression analysis. Use of a package without this limitation would indicate whether further improvements to the model would be possible.

6. The advantages of other multivariate techniques such as discriminant analysis could be investigated.

7. This and other studies have assumed a strong relationship between *site index* and *volume*. This may not be the case, and alternative parameters, possibly more closely related to volume, require consideration in future studies. A different approach, for example, could entail the establishment of permanent sample plots on a range of sites and accorded the same thinning treatments, but there would be severe time constraints.

CHAPTER 3

SITE-FOLIAR NUTRIENT RELATIONSHIPS

Foliar nutrient concentrations expressed as a percentage of dry mass are widely used in forestry for diagnosis of nutrient status, the study of nutrient cycling and fertilizer requirements. The system depends upon the acquisition of foliar nutrient data, usually from extensive fertilizer experimentation on representative sites. In the absence of such experimentation, however, a regional survey of foliar nutrient-tree growth relationships can yield much information in planning a nutritional research programme.

The aims of the study described in this chapter were as follows:

1. Confirm and clarify the role of soil nutrients already observed and described in Ch. 2.

2. Examine relationships between foliar nutrient concentrations and *site index*.

3. Obtain a first approximation of critical levels of foliar nutrient concentrations where non-linear relationships with *site index* make this possible.

4. Identify possible nutrient deficiencies or toxicities and their relationships with site.

5. Compare techniques of foliar nutrient diagnosis for the study area such as critical levels, nutrient ratios and the Diagnosis and Recommendation Integrated System (DRIS).

P.patula has not previously been intensively studied with the above objectives in view, and information on foliar nutrients of this species has not been widely reported in the literature. Few attempts have yet been made to test DRIS in forestry and none have so far been undertaken in *P.patula*.

3.1 LITERATURE REVIEW

The technique of foliar nutrient analysis and its application in forestry has been reviewed by Leaf (1973), Morrison (1974), Schutz (1976) and Van den Driessche (1974). Regional surveys of foliar nutrient levels have frequently been carried out to establish both the relationships with tree growth and the extent of nutrient deficiencies and toxicities (La Bastide and Van Goor, 1970; Norris *et al*, 1980; Sheedy, 1978; Radwan and De Bell, 1980; Raupach, Boardman and Clarke 1969; Truman *et al*, 1983).

The current most widely used technique of foliar diagnosis is that based on the concept of critical levels, defined by Pritchett (1979) as the concentration of an element which is associated with 90% of the maximum yield. However, there are many problems associated with this technique (Schutz and De Villiers, 1988), leading to a quest for new methods. The nutrient ratio concept partially resolves some of these problems (Lambert, 1984), but it is the DRIS technique which appears to offer most hope of success (Beaufils, 1973). Already widely accepted in agriculture, DRIS remains virtually untried in forestry (Schutz and De Villiers, 1988).

Foliar nutrient data for *P. patula* are scant. In the Umzimkulu district of Transkei an attempt was made to relate foliar nutrient concentrations to the growth of *P. patula* (Grey, *et al* 1979; Payn, 1985). A composite sample from two trees was collected from each of 120 plots covering a range of site conditions. Sampling was done after the first spring rains. The regression model to predict site index from foliar nutrients contained the elements K and Si, but explained only 24,6% of the total variation in site index. This disappointing result could possibly be ascribed to the small sample size (two trees) and to the season of collection (spring). The writer has shown that foliar nutrient concentrations in *P. patula* are very unstable in spring and that sampling should always be undertaken in mid- winter (Payn *et al*, 1989).

In Swaziland, Morris (1986) employed foliar nutrient analysis in young trees for interpretation of fertilizer responses. Samples collected from 11 sites indicated that only foliar P and K were correlated with volume increment. *P. patula* foliar nutrient levels in fertilizer experiments and nutrient cycling studies have also been variously reported from East Africa, Madagascar and Brazil (Lundgren, 1978), but with few details given.

3.2 METHODS

Sampling

Foliar samples were collected from eight to ten of the dominant trees per site which had been felled for height measurement on each plot (Ch. 2, para. 2.4). As seasonal variation of foliar nutrient concentrations is minimized by winter sampling (Payn *et al*, 1989), the trees on all sites were felled within a three-week period in the month of June. The most recent, fully-formed needles were sampled from three major lateral branches of the upper third crown and bulked. These samples were in turn bulked for eight to ten trees per site. 147 sites were thus sampled. Mean tree age was 38 years. Samples were placed in polythene bags (to avoid boron contamination possible in the case of kraft paper bags) and cold stored (1-2° C) within 6 hours of collection. They were subsequently dried in glass beakers in a forced-draught oven at 65° C for 48 hours, and ground in a Wiley mill to pass through a 20 mesh sieve. The dried, milled material was then sealed in polythene bags and despatched to the laboratory for analysis.

Nutrient Analysis

All samples were analysed by the S.A. Co-operative Citrus Exchange Ltd. Samples were ashed at 500° C for 3 hours. The ash was treated with 1 N hydrochloric acid, taken to dryness on a water bath and the elements then dissolved in 0,1 N nitric acid and diluted to 100 ml. In the case of boron, a separate sample was analysed to which 0,5 g CaO was added to prevent loss of B during ashing. Samples were analysed for N, P, K, Ca, Mg, Na, S, Cu, Fe, Mn, Zn, B and Al. N, P, S and B were determined colorimetrically on a Technicon Auto Analyzer. All other elements were determined by means of atomic absorption spectroscopy except K and Na, which were done according to the flame emission technique. For Al determinations an air-nitrous oxide flame was used, and for the rest an air-acetylene flame.

Interrelationships

Interrelationships among foliar nutrients were examined using correlation coefficients and principal components analysis. Correlations were also obtained for relationships between foliar and soil nutrients, and between foliar nutrients and *site index*.

Models

Using the regression methods described in Ch. 2, para. 2.5, models were constructed to express the relationships between foliar nutrients and *site* *index*. Individual elements and ratios of elements were examined and compared.

DRIS

DRIS (Diagnosis and Recommendation Integrated System) norms were calculated according to the method of Beaufils (1973), recently reviewed by Schutz and De Villiers (1988). The data base comprised 147 bulk samples with corresponding *site index* as "yield". The sites were ranked according to *site index* and the top third selected as the population of "high-yielding" trees.

The next step is normally to express each element in as many ways as possible, e.g. N % d.m., N/P, NxP. For each sub-population (high-yielders and low yielders) the mean, standard deviation, coefficient of variation and variance (S) of each form of expression are calculated. All those with a significant variance ratio (S_A/S_B) between the low-yield population (A) and the high yield population (B) are retained as forms of expression which are discriminatory. With the number of observations available, however, this was not attempted and all possible nutrient ratios were calculated instead, for both macro- and micro-elements. This situation should be borne in mind when interpreting the results. The mean values of these ratios for high yielding trees are the provisional DRIS norms.

DRIS norms should be tested before being made available for general use. This is normally done through foliar nutrient monitoring of fertilizer experiments, but none suitable for the purpose were available in the study area. Instead each of the sites of high yielding trees was tested in turn against the norms, and DRIS indices computed to confirm their state of nutrient balance. DRIS indices were also computed for a site with poor tree growth to illustrate the possible future use of DRIS in nutrient diagnosis.

3.3 RESULTS

3.3.1 FOLIAR NUTRIENT CONCENTRATIONS

Summary statistics are given in Table 3.1

Table 3.1 Summary statistics for *P. patula* foliar nutrient concentrations

ELEMENT	UNITS	MEAN	RANGE	S.D.	C.V.%
N	%	2,15	1,52-2,58	0,16	7
P	"	0,18	0,13-0,26	0,02	11
K	"	0,87	0,46-1,32	0,17	20
Ca	"	0,26	0,06-0,61	0,11	42
Mg	"	0,17	0,08-0,27	0,43	253
Na	"	0,03	0,01-0,17	0,03	100
S	"	0,16	0,05-0,40	0,07	44
Cu	mg kg^{-1}	5	2-30	2,8	56
Fe	"	113	36-291	43,0	38
Mn	"	1308	276-2790	715,9	55
Zn	"	25	15-43	6,0	24
B	"	24	10-38	6,3	26
Al	"	524	263-1138	172,9	33

The mean values in Table 3.1 for some of the macro-elements appear to be higher than those reported in the literature for other pine species (Morrison, 1974), particularly in the case of *N*. The high foliar *N* mean for *P. patula* is, however, in line with mean values for this species reported for Malagasy (2,06%) by Lundgren (1978), and for Queensland (2,12%) by Morris (1981). The low *Na* values and high values for *Mn* are worthy of note. The minimum value for foliar *P* (0,13%) appears to be considerably higher than the lowest levels recorded for *P. patula* in fertilizer trials in Swaziland, Madagascar and Brazil (Morris, 1986 p 377; Lundgren, 1978). *Ca* and *Cu* fall below the critical levels for these elements given in the literature for other pine species and approach critical levels in the case of *K* (Morrison, 1974). The maximum value for *Mn* is exceptionally high.

As it has already been shown that there are substantial differences in site properties between the major geological substrates (Ch. 1, para. 1.5.2), which affect tree growth (Ch. 2, para. 2.5), foliar nutrient concentrations on the different geological substrates were compared (Table 3.2). As in the case of soil nutrients (Ch. 1, Table 1.10), there were important differences. Calcium levels in particular appear to be strongly influenced by geological substrate. The highest levels were found on *Granite* and *Dolomite*, and the lowest on *Black Reef*. This corresponds exactly with soil *Ca* (Table 1.10). Both foliar and soil *K* were low on *Oaktree* and high on *Granite*. Soil *K* was the highest, by far, on *Dolomite*. In contrast, foliar *K* on *Dolomite* was the second lowest. On *Dolomite*, soil *Al* was the lowest, whereas foliar *Al* was the highest. The minimum values for *Cu* are very low on *Granite, Black Reef, Oaktree* and *Timeball*, and deficiencies are possible. The high foliar *Mn* levels on *Oaktree, Dolomite* and *Timeball* reflect the high manganese in the soil (Ch. 1, para. 1.5). This is illustrated for low and high foliar *Mn* (*Granite* and *Dolomite*, respectively) in Table 3.3.

3.3.2 CORRELATIONS

3.3.2.1 **Interrelationships**

The most important interrelationships among nutrients are shown in Table 3.4. The highest correlation coefficient (-0,54) was for *K-Mn*. Other relatively high correlations were those for *P-B* (0,44), *K-Fe* (0,46), *Ca-Mg* (0,51) and *Fe-Al* (0,51). *K* was correlated with many other nutrients. *K*, *Mg* and *Zn* tended to vary with *Ca* but *Na* varied inversely with *Ca*. Al was negatively correlated with K, Mg, Fe and B.

Relationships among foliar nutrient elements are very complex and difficult to interpret (Schutz, 1976 p. 68), particularly when using correlation coefficients with their limitations as discussed in Chapter 2, para. 5. Principal components and factor analyses revealed that there was little structure among the variables. In PCA the first component accounted for only 20% of the total variation (Table 3.5). Relationships among variables were therefore not strong.

Table 3.2 Foliar nutrient concentrations by geological substrate

ELEMENT	UNITS	GRANITE		SELATI		BLACK REEF		OAKTREE		DOLOMITE		TIMEBALL	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
N	%	2,08	1,92 - 2,30	2,14	2,04 - 2,24	2,18	1,94 - 2,42	2,30	2,06 - 2,56	2,08	1,84 - 2,30	2,22	1,52 - 2,58
P	"	0,18	0,16 - 0,21	0,17	0,14 - 0,19	0,19	0,18 - 0,20	0,17	0,13 - 0,19	0,17	0,13 - 0,20	0,19	0,14 - 0,26
K	"	1,04	0,75 - 1,32	1,00	0,86 - 1,11	0,84	0,67 - 0,98	0,74	0,63 - 0,94	0,78	0,46 - 1,15	0,83	0,56 - 1,11
Ca	"	0,30	0,14 - 0,57	0,20	0,16 - 0,24	0,16	0,11 - 0,31	0,20	0,07 - 0,30	0,34	0,16 - 0,61	0,22	0,06 - 0,46
Mg	"	0,19	0,12 - 0,26	0,19	0,14 - 0,25	0,16	0,11 - 0,24	0,15	0,10 - 0,20	0,16	0,09 - 0,25	0,15	0,08 - 0,27
Na	"	0,03	0,01 - 0,07	0,03	0,02 - 0,05	0,05	0,03 - 0,08	0,04	0,02 - 0,11	0,02	0,01 - 0,05	0,05	0,01 - 0,17
S	"	0,14	0,05 - 0,26	0,18	0,10 - 0,25	0,15	0,08 - 0,23	0,14	0,07 - 0,28	0,15	0,05 - 0,40	0,19	0,07 - 0,40
Cu	mg/kg^{-1}	7	2 - 30	6	4 - 10	5	2 - 8	4	2 - 7	4	3 - 7	5	2 - 8
Fe	"	137	37 - 291	144	128 - 167	121	59 - 174	91	59 - 131	97	36 - 231	104	36 - 201
Mn	"	809	276 - 2187	836	341 - 1673	836	319 - 1719	1676	606 - 2275	1894	847 - 2790	1317	315 - 2678
Zn	"	24	16 - 34	23	15 - 38	20	16 - 27	22	20 - 23	27	17 - 43	27	15 - 42
B	"	24	15 - 38	26	18 - 30	29	25 - 33	23	13 - 33	20	13 - 33	25	10 - 38
Al	"	404	338 - 475	393	263 - 475	486	338 - 688	519	388 - 725	615	300 - 1188	581	313 - 925
n		33		12		7		12		35		48	

Table 3.3 Foliar and soil manganese levels for representative sites on granite and dolomite substrates

Geology	Location	Plot no.	Foliar *Mn* (mg kg^{-1})	A hor. total *Mn* (mg kg^{-1})	A hor. available *Mn* (mg kg^{-1})
Granite	Rosehaugh	P83	336	82	33
Granite	Swartfontein	P92	276	3	2
Dolomite	Brooklands	P69	2790	197	95
Dolomite	Spitskop	P76	2761	428	189

(Total *Mn* : HCl extractant)

(Available *Mn* : NH_4Cl extractant)

Table 3.4 Most significant relationships among foliar nutrients as indicated by correlation coefficients

N-K	-0,24**	*Ca-Mg*	0,51***
N-Ca	-0,29***	*Ca-Na*	-0,34***
N-Na	0,25**	*Ca-Zn*	0,38***
N-B	0,25**	*Ca-B*	-0,20**
P-Mg	0,23**	*Mg-Cu*	0,21**
P-B	0,44***	*Mg-Fe*	0,34**
K-Ca	0,21**	*Mg-Zn*	0,22**
K-Mg	0,26***	*Mg-Al*	-0,21**
K-Na	-0,24**	*Cu-Mn*	-0,27***
K-Cu	0,28***	*Fe-Al*	-0,51***
K-Fe	0,46***	*Zn-B*	-0,22**
K-Mn	-0,54***	*Zn-Al*	0,31***
K-Al	-0,33***	*B-Al*	-0,28***

**significant at 0,01 level

*** " " 0,0001 "

Table 3.5 Principal components analysis of foliar nutrient variables

Principal component	Eigenvalue	Difference	Proportion of variation (%)	Cumulative variation (%)
1	2,63	0,53	20,2	20,2
2	2,08	0,48	16,1	36,3
3	1,61	0,27	12,4	48,7
4	1,34	0,30	10,3	59,0
5	1,04	0,07	8,0	67,0
6	0,97	0,19	7,5	75,0

3.3.2.2 Relationships between foliar and soil nutrients

As soil N and micro-nutrients were not analysed, only the elements shown in Table 3.6 could be examined.

Table 3.6 Correlation coefficients between foliar and soil nutrients

Element	A horizon	B horizon
P	0,23**	0,09
K	0,36***	0,35***
Ca	0,50***	0,45***
Mg	0,25**	0,20**
Al	0,002	-0,08

** significant at 0,01 level
*** " " 0,001 "

The highest correlations were those between foliar and soil *Ca* (A and B horizons), while the lowest were for *Al*. Correlations for the A horizon were higher than those for the B, implying that trees probably obtain most of their nutrients from the topsoil, a trend noticed earlier (Ch. 2, para. 2.5.2.1), and apparent from reviews of the literature (Pritchett, 1979; Ralston, 1964). The relationship between foliar and soil nutrients was logarithmic for *K*, *Ca* and *Mg*. The relationship for *Ca* is shown in Fig. 3.1. Proportionally less *Ca* is apparently taken up by the needles when exchangeable *Ca* in the soil exceeds approximately 200 mg kg^{-1}. The relationship was weaker for *Mg*. It was stronger for the A horizon than the B horizon.

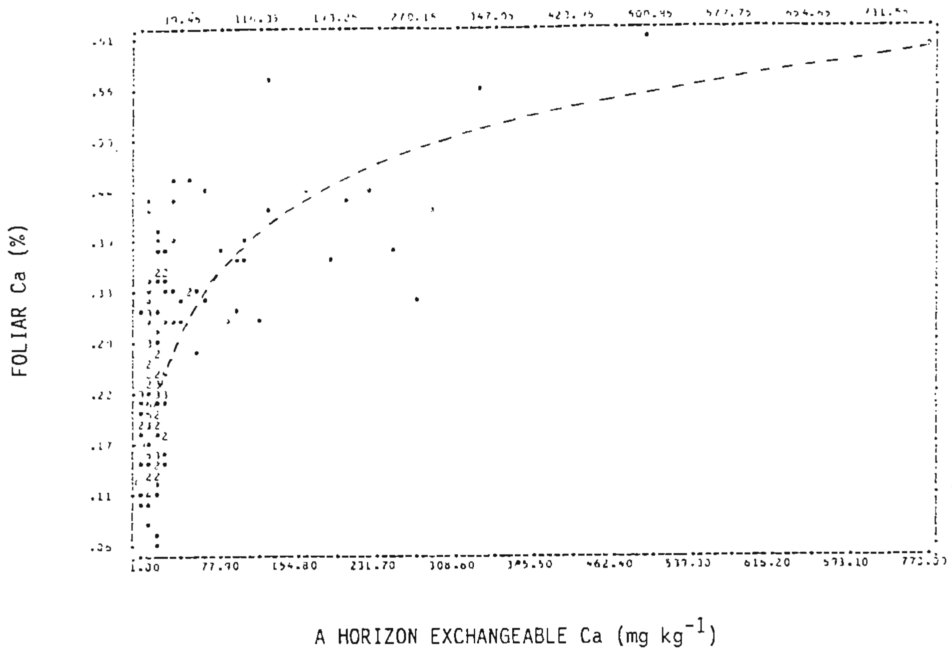


Figure 3.1 Scatter diagram of *foliar Ca* on *soil Ca* (curve hand-fitted).

3.3.2.3 Relationships with other variables

Significant correlation coefficients for site factors other than those already discussed above, as well as stand factors such as age, stocking, tree size and seed source, were generally low (Appendix 9).

Foliar *Ca* was correlated with most site factors, followed by *Mg*, *Na* and *Al*. Factors correlated with *Ca* and *Mg* were inversely correlated in the case of *Na*. *Ca* was negatively correlated (r = -0,5) with *rainfall*. High levels of *N* and *Ca* were associated with high *organic carbon* in the soil. *P* and *Mg* were correlated with all expressions of solar *radiation index*. Soil texture variables were correlated with *K*, *Mg*, *Cu* and *Mn*.

No foliar nutrient elements were correlated with *stand density* and only *Fe* and *Al* had any relationship with tree *age* (29 to 47 years). Several elements were correlated with tree size (*D.B.H.*, *volume*), e.g. *boron*. The correlation between *Ca* and *form factor* is probably indirect through *site index*, trees on poorer sites possibly having a higher taper.

3.3.2.4 Relationships with site index

Site index correlation coefficients with foliar nutrients are shown in Table 3.7.

Table 3.7 Correlation coefficients between foliar nutrient elements and *site index*.

N	-0,27***	*Cu*	0,03
P	-0,14	*Fe*	0,21**
K	0,34***	*Mn*	0,07
Ca	0,62***	*Zn*	0,19
Mg	0,17	*B*	-0,35***
Na	-0,38***	*Al*	-0,07
S	-0,11		

** significant at 0,01 level
*** " " 0,0001 "

N, K, Ca, Na and *B* were all correlated with *site index*, the coefficient for *Ca* being the largest. The coefficient for foliar *Ca* was higher than that for topsoil exchangeable *Ca* (r = 0,5 : Ch. 2, Table 2.13), confirming the potential of this nutrient for *site index* prediction. The low coefficient for *P* confirms that for topsoil *P* (r = 0,11). *Na* and *B* had a negative relationship with tree growth.

However, when relationships are non-linear, correlation coefficients do not adequately express the association. From scatter diagrams it is apparent that all relationships were linear except those for *Ca*, *Mg* and *Mn*. *Ca* and *Mg* had a logarithmic relationship and *Mn* showed a possible depressive effect on *site index* at high levels (Fig. 3.2). *Mn* appeared to have no effect on growth at levels up to 2 000 mg kg^{-1}. Above this there is a chance that *site index* could be affected. 700 mg kg^{-1} is regarded as the toxic point for foliar *Mn* in *P.radiata* (Adams and Walker, 1974).

3.3.3 SITE INDEX MODELS

3.3.3.1 **Individual foliar nutrient elements**

There were several possible models expressing foliar nutrient relationships with *site index*, the best fit being obtained by Model 3.1 shown in Table 3.8.

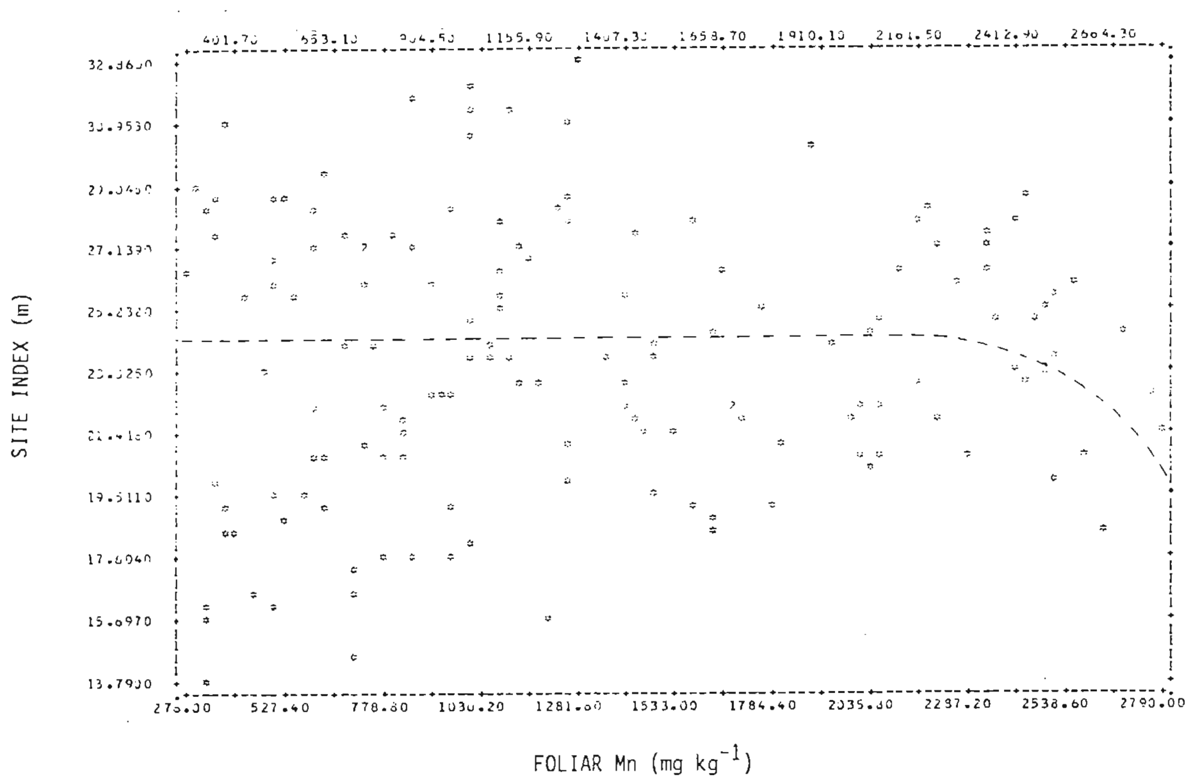


Figure 3.2 Scatter diagram of *site index* on *foliar Mn* (Curve hand-fitted).

Table 3.8 MODEL 3.1: Regression coefficients for individual foliar nutrient elements

X	Regres. coeff.	S.D.	Stdd. coeff.	t-value	Probability
log *Ca*	15,74562	1,52	0,73	10,39	<0,00001
log *Mg*	-10,40891	2,52	-0,29	4,14	0,00006
K	6,62537	1,39	0,28	4,78	<0,00001
B	-0,15002	0,04	-0,23	4,04	0,00009
Al	-0,00285	<0,01	-0,12	2,02	0,04544
Intercept	24,30789	4,54			
R^2 = 0,5957		S.E. = 2,624			

The lowest eigenvalue was 0,34684, indicating no serious multicollinearity among the variables in the model, as already indicated by PCA (Table 3.5). The coefficient of determination was 0,5957, which is very close to, but slightly less than, that obtained for the model with soil analytical variables (Model 2.3: R^2 = 0,6020).

3.3.3.2 Ratios of foliar nutrient elements

Interactions between foliar nutrient elements in the form of ratios are widely recognized as being of importance in tree nutrition, (Weetman, 1981; Schönau and Herbert, 1983). Ratios of the elements in Model 3.1 together with some of those commonly cited in the literature, were investigated for their potential in predicting *site index*. From best-subsets regression analysis the following ratios emerged as the most important:

Ca/Mg *B/K* *K/Mg* *Al/P*

Log transformations were tested but did not improve the model (Table 3.9). Only the *Ca/Mg* and *B/K* ratios appeared in the final model. The R^2 of Model 3.2 was slightly lower than that of Model 3.1. Foliar nutrient ratios have therefore not improved *site index* prediction.

Table 3.9 MODEL 3.2: Regression coefficients for foliar nutrient ratios.

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Ca/Mg	3,25882	0,66	0,44	4,92	<0,00001
B/K	-0,14329	0,02	-0,34	5,98	<0,00001
log *Ca*	4,52990	1,94	0,21	2,34	0,02080
Al	-0,00387	<0,01	-0,16	-2,90	0,00438
Intercept	27,31957	4,15			

R^2 = 0,5770 S.E. = 2,708

3.3.3.3 Choice of dependent variable

The dependent variable chosen for the foliar nutrient models was the same expression of tree growth as that used for the models in Chapter 2, viz. *top height at 20 years* based on the mean height of 30% of the trees with largest D.B.H. As it was by no means certain that this was necessarily the best one for foliar nutrient models, the following dependent variables (as described in Ch. 2 para. 2.4.3) were compared, using the independent variables of Model 3.1:

Y_1	$HT20_{10}$	:	As defined above
Y_2	$HT20_5$	:	As above but based on the mean of 5 trees.
Y_5	$HT30$	:	Top height at 30 years
Y_6	$HT40$	:	Top height at 40 years.
Y_7	$V20_{MAI}$	:	MAI-20 index.

The dependent variables are compared in Table 3.10. With the highest R^2, Y_1 is confirmed as the most appropriate dependent variable.

Table 3.10 R^2 values for models with the same subset of independent variables but different dependent variables.

Y		R^2
Y_1	$HT20_{10}$	0,5957
Y_2	$HT20_5$	0,5650
Y_5	$HT30$	0,5690
Y_6	$HT40$	0,1136
Y_7	$V20_{MAI}$	0,5420

3.3.4 DRIS

Foliar nutrient concentrations for the sub-population of high-yielding trees are given in Appendix 10. This sub-population comprised the 48 best sites with regard to *site index*. Data for each site represented the mean of 8-10 trees, thus reducing genetic variation. The high-yielding sub-population comprised all sites with *site index* over 26 m at 20 years. Although this data bank is small by DRIS standards, the fact that sampling was confined to a three-week period in winter does remove one of the sources of variation. The DRIS norms calculated from these data are probably more accurate as a result, but will be limited in their application to trees which have likewise been sampled only in winter. This is not necessarily a disadvantage, but in time the data bank should be augmented with analyses covering all variation in season and tree age.

DRIS norms computed from the data bank described above are given in Appendix 11. These norms are provisional until subjected to testing in fertilizer experiments, and until augmentation of the data bank produces possible refinements. Although based on data from a restricted geographic location, the norms may well be applicable further afield, subject to testing.

DRIS indices for high-yielding sites are shown in Table 3.11. It can be seen that the indices for individual elements were all numerically close to zero and the elements were therefore neither deficient nor in excess. The condition of nutrient balance of trees on these high-yielding sites and their suitability for use as a data base for the calculation of provisional DRIS norms for the Eastern Transvaal thus appear to be confirmed.

Table 3.11 DRIS indices for trees on mean high-yielding sites

Element	DRIS index
N	-2,5524
P	-2,3870
K	-2,8931
Ca	-2,7358
Mg	-1,8728
Na	-0,6228
S	-0,1281
Cu	0,6132
Fe	0,2252
Mn	3,1255
Zn	2,0654
B	2,5041
Al	4,6587
Sum	0,0001

To illustrate how DRIS could be used, indices were calculated and compared with foliar nutrient concentrations for a *P.patula* stand of low *site index* (18 m at 20 years) selected at random (Table 3.12).

From Table 3.12 the following conclusions could be drawn:

1. The sum of the absolute values of the DRIS indices is 270, indicating severe nutrient imbalance,which is probably reflected in the *site index* of only 18 m.

Table 3.12 Comparison of foliar nutrient concentrations and DRIS indices for *P.patula* on a poor site (S.I. = 18 m)

Element	Foliar nutrient concentration	DRIS indices
N	2,28%	12
P	0,18"	10
K	0,97"	12
Ca	0,08"	-78
Mg	0,09"	-25
Na	0,02"	6
S	0,22"	21
Cu	5 mg kg^{-1}	6
Fe	67 "	-12
Mn	389 "	-19
Zn	20 "	-2
B	38 "	52
Al	525 "	15
Sum of the absolute values:		270

<u>Order of requirements</u>:

Ca> Mg> Mn> Fe> Zn> Na> Cu> P> N> K> Al> S> B

2. The most limiting nutrient is Ca, followed by Mg. As both these elements have already been found to be highly correlated with *site index*, this diagnosis could be correct. Fertilization with dolomitic lime would be recommended.

3. N, P and K are sufficient. A standard N-P-K fertilizer application would be unlikely to produce a response.

4. Manganese levels in the soils are extremely high, and the low index for *Mn* is relative to a high value for the norm. It is unlikely to reflect a deficiency in this case.

5. Boron is the element in least demand, and could be in oversupply.

3.4 DISCUSSION

3.4.1 FOLIAR NUTRIENTS AND SITE INDEX

3.4.1.1 Nitrogen

Although the range in foliar *N* concentrations was fairly wide (Table 3.1), *N* had a low correlation with *site index* (Table 3.7) and did not appear in any of the prediction models. There was also little variation between geological substrates (Table 3.2). N deficiency does not therefore appear to be likely on most sites. Even for trees on a poor site, the DRIS diagnosis indicated that N was adequately supplied (Table 3.12).

3.4.1.2 Phosphorus

Similarly to *N*, *P* appears to be well supplied (Table 3.1), with the minimum level being well above the lowest recorded for *P.patula* elsewhere. Support for this finding arises from the low correlation between foliar *P* and *site index* (Table 3.7), the absence of *P* from any of the prediction models (Tables 3.8, 3.9) and the indication by the DRIS diagnosis of trees on a poor site that P was adequately supplied. Foliar P is aften closely related to Bray 2 extractable soil P (Wells, 1965). However, the low correlation between foliar *P* and Bray 2 *P* (Table 3.6) would seem to indicate that Bray 2 may not be the most appropriate extractant of P in this case.

These findings lend additional weight to the argument that *P.patula* in the study area may be able to obtain sufficient P for most of its requirements from sources other than Bray 2 P, possibly as organic P (Ch. 2, para. 2.6.1). Final confirmation of this can, however, only be obtained through properly designed fertilizer trials in the area.

3.4.1.3 Potassium

The high foliar *K* levels of trees on granite-derived soils (Table 3.2) can be ascribed to the K minerals present in this rock type. Foliar *K* was lowest in trees on soils of the Oaktree and dolomite substrates. While Oaktree-derived soils are correspondingly low in *K* (Table 1.10), dolomite-derived soils are, in marked contrast, the highest by far in *K* (Table 1.10). A possible explanation for this anomaly may lie in the high correlation between foliar *K* and *Mn* (Table 3.4). The correlation coefficient was, in fact, the highest of all for relationships among foliar nutrient elements. This could indicate a K-Mn antagonism, uptake of K being suppressed in the presence of high Mn levels. There may, however, be other explanations. Dolomite-derived soils (which are the highest in Mn) may, for example, contain K-fixing clay minerals (e.g. vermiculite) which would reduce the availability of K for uptake by tree roots. It should be noted, however, that it is not only foliar *Mn* which is highest in trees on dolomite-derived soils, but also foliar *Ca* and *Mg* (Tables 1.10 and 3.2). If K-fixation were the problem then one would have expected foliar *K* also to have had high negative correlation coefficients with *Ca* and *Mg*, by association. These correlation coefficients were, in fact low and positive (Table 3.4). Similarly, as the Oaktree Formation (part of the Chuniespoort Group) is also high in manganese, a K-Mn antagonism could be partly responsible for the very low foliar *K* recorded for trees on Oaktree-derived soils. No reference to this problem could be found in the literature. Verification of the K-Mn antagonism is required.

There was a logarithmic relationship between foliar *K* and soil available *K*, implying that less K is taken up by the needles at high soil K availability. At least a partial explanation for this relationship could be the K-Mn antagonism, if it can be verified, as uptake of K is low on the soils with the highest availability of K.

Although foliar *K* was not highly correlated with *site index* (Table 3.7), it nevertheless appeared as an important variable in Model 3.1 in a linear relationship with *site index*, and in the B/K ratio in Model 3.2. According to Table 3.1, K may be deficient on some sites. Trees on the site for which a DRIS diagnosis was run, however, appeared to be adequately supplied with K (Table 3.12).

3.4.1.4 **Calcium**

There is some evidence that the availability of exchangeable Ca in the soil is more dependent on parent material than on rainfall (Ch. 1, para. 1.5.2.5). Foliar *Ca* was well correlated with soil exchangeable *Ca* (Table 3.6), and also followed the same trend with respect to *geology* (Table 3.2). It is therefore not clear why foliar *Ca* should be correlated with *rainfall* (Appendix 9) while soil exchangeable *Ca* is only poorly correlated. The general uncertainty of correlation coefficients for establishing relationships should, however, be taken into consideration.

Ca deficiency is a likely problem in *P.patula* in the study area (Table 3.1), and foliar *Ca* proved to be correlated with *site index* (Table 3.7). *Site index* was more highly correlated with foliar *Ca* (r = 0,62; Table 3.7) than with soil exchangeable *Ca* (r = 0,5; Ch. 2, Table 2.13). This may be a confirmation of the logarithmic relation between foliar *Ca* and soil exchangeable *Ca*, in that trees take up only the amount of Ca that they require and that this quantity is related to *site index*. The presence of *Ca* in both Model 2.3 (soil) and Model 3.1 (foliar) confirms that *site index* was closely related to variation in the concentration of this element. As in the case of Model 2.3, *Ca* was by far the most important variable in the foliar nutrient model. The logarithmic transformation of *Ca* confirms the trend already detected via the scatter diagram, and already apparent in Model 2.3 (soil). The log arithmic relationship enables an estimate of the critical level for foliar *Ca* to be made. This estimate is likely to be more accurate if the influence of other key foliar nutrients can be included but held constant at their mean values, i.e. via the model, rather than via the scatter diagram. If the "critical level" is defined as the concentration which is associated with 90% of the maximum yield (Pritchett, 1979), then this point cannot, with any certainty, be determined from Fig 3.3. However, it is apparent from Fig. 3.3 that *site index* is severely affected below foliar *Ca* concentrations of about 0,25%. This may thus be accepted as a provisional critical level.

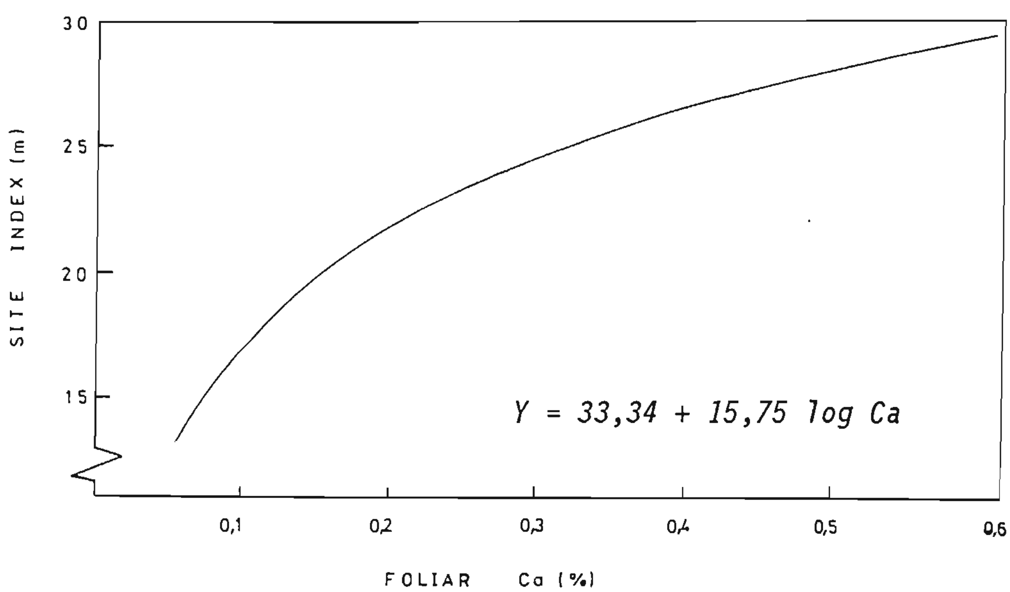


Figure 3.3 Trend graph of *site index* on *foliar Ca*, ex Model 3.1 (other variables held at mean values).

The variable log *Ca* also appeared in Model 3.2 (nutrient ratios), but the *Ca/Mg* ratio appeared to be a more important predictor of *site index*. Confirmation of the importance of Ca was obtained by the DRIS diagnosis of trees on a poor site (Table 3.12), which indicated that Ca was the most limiting nutrient.

3.4.1.5 **Magnesium**

There was a wide variation in foliar *Mg* among sites (Table 3.1), but not among geological substrates (Table 3.2). There was a logarithmic relationship between foliar *Mg* and soil exchangeable *Mg*, but the correlation was low (Table 3.6).

In spite of a low correlation with *site index* (Table 3.7), *Mg* was an important variable in prediction models. In Model 3.1 the relationship with *site index* was logarithmic, while in Model 3.2 it was the most important predictor in the form of the *Ca/Mg* ratio. As in the case of the soil model (Model 2.3), the regression coefficient for log *Mg* in Model 3.1 was negative. Once again the question arises (Ch. 2 para. 2.6.1) whether an oversupply of Mg is indicated, or whether the sign may be incorrect due to multicollinearity. There is also the possibility of an Mg-K antagonism, but this is unlikely as the correlation between these two elements was low and positive. As in the case of Model 2.3, log *Mg* was correlated with log *Ca* in Model 3.1 (r = 0,60), although standard tests of multicollinearity were negative. Other pointers in favour of an incorrect sign are the positive correlation coefficients for both soil exchangeable *Mg* and foliar *Mg* (Tables 2.13, 3.7), the general "unlikelihood" of an oversupply of Mg according to the literature, and the diagnosis of Mg as the second most limiting nutrient in trees on a poor site using the DRIS method.

3.4.1.6 **Other nutrients**

Na

The low mean value for foliar *Na* (Table 3.1) tends to confirm the leached status of the soil with regard to this element (Ch. 2, para. 2.3.2.3). *Na* was not highly correlated with *site index* (Table 3.7) and did not appear as a variable in any of the prediction models.

S

Although there was a wide variation in *S* (Table 3.1), it did not appear to be related to *site index*. S was one of the nutrients in least demand in the DRIS evaluation of trees on a poor site (Table 3.12).

Cu

Foliar *Cu* fell below critical levels on some sites (Tables 3.1, 3.2) but it did not appear in any prediction models, possibly due to deficiencies not being sufficiently widespread.

Fe

Foliar *Fe* did not appear to be related to *site index*.

Mn

Foliar levels of *Mn* were exceptionally high on soils derived from rocks of the Chuniespoort Group, but did not, however, reach toxic proportions for *P.patula* except at concentrations above approximately 2000 mg kg^{-1} (Fig 3.2). This effect was apparently not strong enough for *Mn* to be included in any prediction models. The high foliar *Mn* concentrations appear to be quite unusual, Mn deficiencies being more commonly reported in the literature than toxicities (Lange 1969; Radwan and de Bell, 1980). This may explain why references, either to the possible suppression of K uptake by Mn (para 3.4.1.2), or to the problems of particle size analysis of soils high in Mn (Appendix 7.1), could not be found.

Zn

Variation in *Zn* levels did not appear to be related to *site index*.

B

An apparent depressive effect on tree growth of B was indicated by the negative correlations between foliar *B* and *site index* (Table 3.7), *D.B.H.* and *volume* (Appendix 9), the negative regression coefficients in Models 3.1 and 3.2, and the fact that B was the element in least demand in the DRIS diagnosis of trees on a poor site (Table 3.12). This apparent oversupply of B was unexpected. B deficiencies in plantation tree species are common in the sub-tropics, particularly in areas prone to drought, and has been reported in the case of *P.patula* in countries such as Brazil and Tanzania (Schutz, 1976). B deficiencies in *P.patula* in southern Africa were suspected in the past and in some instances borax was even applied as a fertilizer. Induced B deficiencies in pine and spruce as a result of fertilization with N or N plus lime have been reported in Sweden (Möller, 1983; Aronsson, 1983). No reports of any growth reduction due to a natural excess B, however, could be found in the forestry literature. It is possible that *P.patula* is, in fact, more sensitive to high B levels than are other species. The maximum level of 38 mg kg^{-1} (Table 3.1) is high but not excessively so for forest tree species in general, but could well be high for *P.patula*. No confirmation of this could be found in the literature. Table 3.2 shows that the highest levels of *B* are found on quartzite parent material. Geochemistry could play a role, but B analyses of rock types in the Eastern Transvaal are not available. However, in Europe quartzites and shales are often high in B whereas limestones and granites are usually low (Wikner, 1983). According to Wikner, acid exudates from roots under wet conditions could release unavailable B. The generally thick litter layers commonly found on quartzite coupled with the high rainfall and wet conditions found along the Escarpment could combine to release B from quartzite more rapidly than from other rock types lower in B. The role of B in *P.patula* nutrition requires further attention, for example through pot trials.

Al

Foliar *Al* was one of the variables included in *site index* prediction models. As in the case of soil exchangeable *Al* (Ch. 2, para. 2.6.1.1), foliar *Al* was negatively related to *site index* (Table 3.7, Models 3.1 and 3.2). It was also negatively correlated with foliar *K*, *Mg*, *Fe* and *B* (Table 3.4). However, foliar *Al* was poorly correlated with soil exchangeable *Al* (Table 3.6), for example. Although foliar *Al* was highest on dolomite-derived soils (Table 3.2), exchangeable *Al* in these soils was the lowest. The reason for this is not known.

3.4.2 CHOICE OF DEPENDENT VARIABLE

Referring to Table 3.10, it is of interest that foliar nutrient concentrations in samples taken from trees as old as 38 years (mean age of trees sampled) were able to predict *top height at 20 years* more accurately than *top height at 30 years* or *40 years*. The difference between *HT20* and *HT30* was only slight. Within the range of tree ages sampled (29 - 47 years), age therefore did not appear to affect foliar nutrient levels for most elements. This would tend to confirm the weak correlations between foliar nutrient concentrations and *age* already found (para. 3.3.2.3). In New South Wales, Australia, foliar nutrient concentrations of *P.radiata* were not affected by stand ages over 16 years (Lambert and Turner, 1988). Morris (1986) found that foliar Ca increased between four and twelve years in *P.patula* grown in Swaziland, this age span covering the period of canopy closure. It thus appears that *top height at 20 years* can be predicted with equal accuracy from foliar nutrient concentrations of samples collected from trees of any age over 20 years.

Not a great deal of importance can be attached to the difference between $HT20_{10}$ and $HT20_5$. The interpretation is that foliar analysis of a bulk sample from 10 trees predicts the growth of those 10 trees slightly better than that of the largest 5 of those 10 trees. $V20_{MAI}$ was not as well predicted as $HT20_{10}$, but the difference in R^2 was less than in the case of site models (Table 2.21).

3.5 CONCLUSIONS

The conclusions below are made with the knowledge that foliar nutrient concentrations are fairly gross measurements, sensitive to a wide variety of influences such as the ratios of nutrients in the soil solution at the particular time, genotypic variation in tree physiology, and many other factors. The system is thus a complex one.

3.5.1 FOLIAR NUTRIENT CONCENTRATIONS AND VARIATION

1. *P.patula* appears to have higher mean foliar nutrient concentrations for macro elements than most other pine species.

2. Foliar nutrient levels of many elements varied according to geological substrate and generally followed the same trends as soil nutrients in this regard.

3. Foliar and soil nutrients were found to be closely related for some elements, the correlations being higher for A than for B horizons. As it has already been shown that *site index* was more highly correlated with A than with B horizon soil nutrients (Chapter 2, para. 2.5.2.1), the implications are that the trees probably obtain most of their nutrients from the topsoil.

4. Foliar nutrients were poorly correlated with other site and stand variables.

5. A principal components analysis showed that there was little structure among foliar nutrient variables.

3.5.2 FOLIAR NUTRIENTS AND SITE INDEX

1. N deficiency did not appear to be a problem in stands over 20 years of age in the study area.

2. There were indications that P was also adequately supplied, possibly from the soil organic fraction, as Bray 2 extractable *P* was only weakly related to *site index*.

3. On the other hand, K deficiencies are likely, as *K* was an important variable in *site index* prediction models. Foliar *K* varied according to geological substrate, but in strong contrast to soil exchangeable *K*, foliar K was lowest on soils derived from dolomite. A high, negative correlation between *K* and *Mn* leads one to suspect that uptake of *K* may be suppressed by Mn, which is extremely high in dolomite-derived soils.

4. Ca has emerged as the nutrient with the closest relationship with *site index*. It was the most important variable in models to predict site index from both soil and foliar nutrients. In addition, a DRIS diagnosis run on trees growing on a randomly selected poor site confirmed that Ca was the most limiting nutrient. As in the case of soil *Ca*, foliar *Ca* had a logarithmic relationship with *site index*. Foliar *Ca* below approximately 0,25% was associated with severely depressed height growth. The logarithmic trend in the relationship between soil and foliar *Ca* indicated that proportionally less *Ca* was taken up by the needles when exchangeable *Ca* in the soil exceeded approximately 200 mg kg^{-1}. Foliar *Ca* was more highly correlated with *site index* than was soil *Ca*. Foliar *Ca* was highest in trees on granite and dolomite-derived soils and lowest on Black Reef, corresponding exactly with soil exchangeable *Ca*.

5. *Mg* was also closely related to *site index*, appearing in both the soil and foliar models to predict *site index*. The relationship with *site index* was logarithmic. The regression coefficients in both the soil and the foliar models were negative, implying an oversupply of this nutrient. However, there was some evidence that the regression coefficients had the wrong sign in both models, and that Mg is generally deficient rather than the opposite.

6. *Na*, *S*, *Cu*, *Fe* and *Zn* did not appear to be related to *site index* variation. Foliar *Na* concentrations were very low, tending to confirm the leached status of the soils. Cu deficiency may be a possibility on a few sites.

7. *Mn* concentrations in the needles of *P.patula* were found to be extraordinarily high, without affecting growth except at the very highest levels. This is attributed to the known excessively high soil *Mn* levels on some geological substrates. However, *Mn* did appear to affect *site index* indirectly through the possible suppression of K uptake, as described in 3. above.

8. *B* levels in the soil were not determined but it appeared as an important variable in foliar models. Both the correlation and the regression coefficients were negative, implying an oversupply of this element. This was further confirmed by a DRIS diagnosis of trees on a poor site. B deficiencies in many countries have been widely reported in the literature, but this is the first known case of an evident oversupply of B. Foliar *B* was highest on Black Reef, which seems plausible.

9. As in the case of soil exchangeable *Al*, foliar *Al* was negatively related to *site index*. Foliar and soil exchangeable *Al* were, however, poorly correlated.

10. The "best" model to predict *site index* of *P.patula* from foliar nutrients contained the variables log *Ca*, log *Mg*, *K*, *B* and *Al*, which explained nearly 60% of the total variation in *site index*. Nutrient ratios were less effective.

11. DRIS was shown to have potential for diagnosis of the nutritional status of trees, with many advantages over more conventional methods. Provisional DRIS norms were computed, based on winter sampling. A DRIS diagnosis of trees on a poor site indicated that Ca was the most limiting nutrient, followed by Mg. N, P and K appeared to be sufficient, whereas B was the element in least demand.

3.5.3 DEPENDENT VARIABLES

1. *Top height at 20 years* based on the mean height of the 10 trees of largest D.B.H. (i.e., *site index*) was confirmed as the most appropriate dependent variable for use in prediction models with foliar nutrients.

2. Within the range of tree ages sampled (29 - 47 years), foliar nutrient concentrations appeared to be unaffected by age. A comparison of models to predict *top height* at different ages showed that foliar samples taken from trees over 30 years of age predicted *top height* at 20 years better than *top height* at ages above 20 years.

3.5.4 FURTHER RESEARCH

This study has identified the need for research in the following:

1. Confirmation that P requirements are being met from sources other than Bray 2 P, and identification of those sources.

2. The role of Mn in the possible suppression of K uptake.

3. Confirmation that Mg is generally deficient rather than in oversupply.

4. The extent of Cu deficiencies.

5. Confirmation of the possibility that B could be in oversupply.

6. The role of Al in uptake of other nutrients.

7. Testing of the provisional DRIS norms in appropriate fertilizer experiments and enlargement of the DRIS data bank.

CHAPTER 4

SITE-LITTER RELATIONSHIPS

Litter is one of the most critical pools in the nutrient cycle and is a key to maintaining the productivity of plantation ecosystems (Gresham, 1982; Squire *et al*, 1985). As the stand matures, the importance of the litter layer in the nutrient cycling process increases until it can eventually replace the mineral soil as the principal source of nutrients (Von Christen, 1959; Jorgensen, *et al*, 1980). Other important roles of the litter layer include insulation of the soil from extremes in temperature and moisture, mechanical protection from rain drop impact and erosional forces, and improvement of water infiltration (Metz, 1958; Pritchett, 1979).

However, the beneficial role of the litter layer can be reversed into a potentially harmful one if the factors which promote decomposition processes slow down markedly for some reason. If the annual rate of decomposition drops below the annual amount of litter fall, a build-up of raw humus takes place resulting in what is referred to as a "mor" layer (Handley, 1954; Pritchett, 1979). Mor layers are regarded as a threat to site productivity, as nutrients are immobilized, potentially harmful organic acids are released, moisture penetration is reduced, and there are practical problems such as restriction of access, increased fire danger and lack of wind firmness in newly planted trees (Von Christen, 1959; Lamb and Florence, 1975; Schutz, *et al*, 1983; Morris 1986).

An increase in forest floor mass of 37% between first and second rotations of *P.patula* has been recorded in Swaziland, leading to an estimated 9% decline in the productivity of stands on high altitude sites (Morris, 1984, 1986). This was thought to be due to the accumulation and immobilization of nutrients in thick litter layers, causing a greater drain on the site than even log removal (Morris 1986 p 287).

Abnormally thick mor layers under *Pinus patula* stands have also been reported in the Eastern Transvaal (Von Christen 1959, 1964; Schutz, 1982; Schutz *et al*, 1983) (Fig. 4.1). The maximum thickness so far recorded was between 60 and 65 cm under a mature stand of *P.patula* on Ceylon State Forest (over 300 t ha^{-1} oven dry mass). The thickest litter layer that could be found recorded in the literature was 46 cm for a sub-alpine natural stand of *P.contorta* in Washington State, U.S.A. (Woodard and Martin, 1980). This would give the

Eastern Transvaal mor layers the dubious distinction of being possibly the thickest in the world. Decomposition is so slow that the pre-afforestation grasses remain preserved beneath the mor in some cases. Thick litter layers under natural stands of *P.patula* in Mexico are apparently sometimes found on level terrain (G. Donahue, pers. comm.), but are usually kept in check by frequent wildfires (W. Dvorak, pers. comm.)

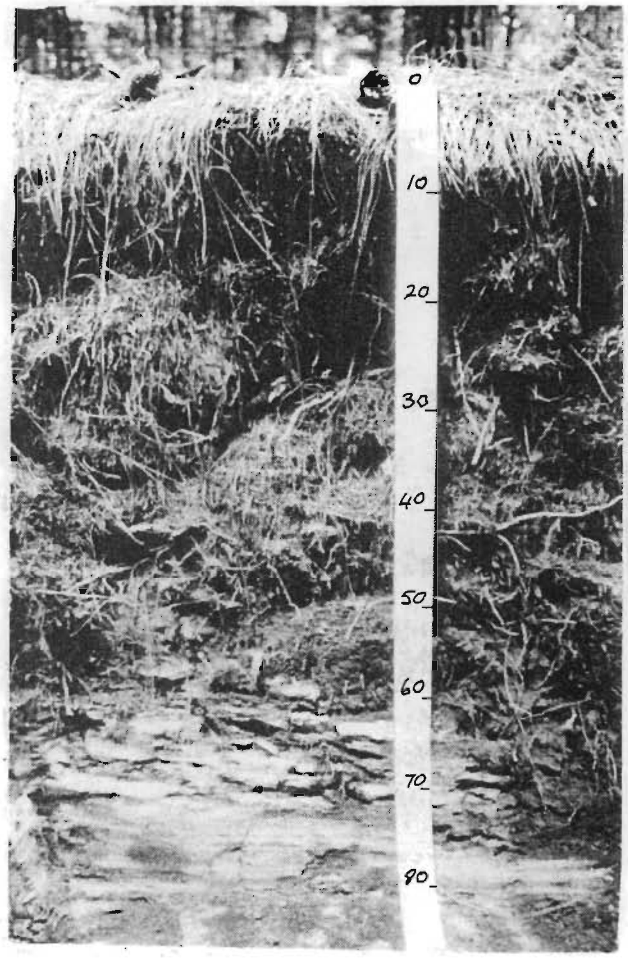


Figure 4.1 45 cm mor layer in a 50 year old first rotation stand of *P.patula* on Ceylon S.F. The soil is of the Mispah form on partially decomposed shales of the Timeball Hill Fm.

A study of site-tree relationships would hardly be complete without consideration of this problem. The main purpose of the investigation described in this chapter was to identify the key environmental factors associated with variation in litter thickness, and thereby obtain a clearer understanding of the possible causes and effects of excessive litter accumulation.

4.1 REVIEW OF FACTORS AFFECTING LITTER DECOMPOSITION

Some factors found to influence litter decomposition (and thus litter accumulation) are reviewed in Table 4.1. From the literature it is apparent that decomposition is largely influenced by factors which control micro-organism activity. On a macro-scale evaporation and latitude have a major influence. On a micro-scale a wide variety of factors play a role, and the evidence for relationships is often conflicting. No clear indications emerge which might explain the development of thick litter layers under *P.patula* in southern Africa. Work in this region has been done by Von Christen (1959, 1964), Higgs (1981), Schutz *et al* (1983) and Morris (1986), whose finding are reviewed in Table 4.1. Only the work of Von Christen (1964) and Schutz *et al* (1983) have so far been published.

Table 4.1 A review factors affecting litter decomposition

Factor	Yes	No	Remarks	Source
1. Annual actual evapo-transpiration	X		Continental scale	Meentemeyer, 1984
2. Latitude	X		Faster with lower latitude	Olson, 1963
3. Temperature	X		Faster with high temperature	Armson, 1977; Von Christen, 1959
4. Altitude	X		Faster with lower altitude	Morris, 1986
5. Rainfall	X		Slower under dry conditions	Witkamp & Van der Drift, 1961
		X		Duffy *et al*, 1985
6. Wet sites	X		In the tropics	Olson, 1963; Pritchett, 1979
7. Mist	X		Slower in misbelt	Von Christen, 1959
8. Site quality		X		Florence & Lamb, 1974
	X		Greater accumu-lation on better sites	de Ronde, 1984; Hamilton and Krause, 1985; Versfeld, 1981
		X		Schlatter & Gerding, 1984
9. Soil type	X			Florence & Lamb, 1974

Table 4.1 (continued)

Factor	Yes	No	Remarks	Source
10. Soil texture	X		Slower on fine texture	Pritchett, 1979
	X		Faster on fine texture	Florence & Lamb,1974
11. Soil pH	X	X	Conflicting evidence	Handley, 1954
12. Soil bases	X		Slow with low base status	Von Christen, 1959, 1964
13. Soil P	X		Slow with low P	Pritchett, 1979
14. Soil Al	X		Slow with high Al (tropics)	Pritchett, 1979
15. Litter fall		X	Uniform for similar sites	Florence & Lamb, 1974 Pritchett, 1979
16. Litter lignin	X		Slow with high lignin	Meentemeyer, 1984
17. Litter N	X		Slow with low N	Von Christen,1959 Carlyle, 1986
18. Litter lignin: N ratio	X		Slow with high ratio	Carlyle, 1986
19. Litter C:N ratio	X		Slow with high ratio	Carlyle, 1986
20. Litter pH	X		Slow with high acidity	Carlyle, 1986
21. Litter bases	X		Slow with low base status	Von Christen, 1959
22. Litter waxy cuticles	X		Inhibits decomposition	Higgs, 1981
23. Litter celluloses	X			Handley, 1954
24. Litter mycorrhizae	X		Inhibit decomposition	Gadgil & Gadgil, 1975
25. Stand stocking	X		Slow with greater N ha^{-1}	Von Christen, 1959 Klemmedson *et al*, 1985
		X		Schutz *et al*, 1983
26. Fire		X	Protection causes accumulation	Gholz, *et al*, 1985

4.2 METHODS

Litter classification

Apart from the problem of litter accumulation under forest stands in Germany (Baule and Fricker, 1970), the forest floor and its biological processes attracted little, if any, attention from soil scientists until the mid-twentieth century (Armson, 1977 p 79). Even now, a science of litter has not been developed and we do not even have an unambiguous definition of forest litter (Sapozhnikov, 1985).

Consequently there is also little unanimity on systems of classification (Pritchett, 1979 p 52), and horizon designation is usually done according to one of two systems. The first is a stratification into L, F and H layers. The L or litter layer consists of unaltered dead remains of plants and animals. The F or fermentation layer is a zone immediately below the L layer consisting of partly decomposed organic materials sufficiently well preserved to permit identification as to origin. The H or humus layer consists largely of well-decomposed, amorphous organic matter, immediately below the F layer. The second is a simpler designation in use by the United States Soil Conservation Service and also adopted by the South African binomial soil classification system (Macvicar *et al*, 1977), into O1 and O2 layers. The O1 horizon comprises largely undecomposed organic debris in which the original form of most vegetative matter is visible to the naked eye. The O2 horizon comprises partially decomposed organic debris in which the original form of most plant and animal matter cannot be recognized with the naked eye. In this study the South African binomial classification system was used.

Sampling

The study was conducted on the 159 sites under mature stands of *P.patula* described in Ch. 2, para. 2.2. The sites covered a wide variety of litter depths and environmental conditions. According to Arp and Krause (1984), the forest floor is characterised by high spatial variability of physical and chemical properties, and sampling guidelines are generally not available. The Eastern Transvaal was found to be no exception, and litter depth was extremely variable over small distances, due mostly to disturbance caused by the extraction of logs from thinnings, from the action of bush pigs turning over the litter in search of food, and from heterogenous ground vegetation. In addition litter is thickest near the base of widely spaced trees (Schutz, *et al*, 1983). Under these conditions a large number of samples would be required for the estimation of litter depth on each site. As resources were not available for this, litter thickness in centimeters was taken as the average profile thickness exposed from the undisturbed sides of the L-shaped soil pit described in Chapter 2, para. 2.2.2. A bulk litter sample for analysis was taken from the three extremities of the L. On most sites it was found that the 02 horizon was absent, ill-defined (especially as a result of the disturbances described above), or less than 1 cm in thickness. The ill-defined 02 horizon is also typical of southern pines in the U.S.A. (Pritchett, 1979 p 57). Consequently litter thickness was measured as total thickness (01 + 02). As it proved very difficult to separate the 01 and 02 horizons when collecting samples for analysis, no distinction was made and the 01 and 02 horizons were combined.

Rooting in the litter was prolific in the thicker layers and was assessed on a visual scale of from 1 to 3. No attempt was made to separate live roots from litter samples. Virtually all litter samples were taken from first rotation, mature stands of average age 38 years.

Laboratory analysis

55 samples covering the range in *site index* were analysed chemically and for pH. Samples were dried, milled and analysed for N, P, K, Ca, Mg, Na, S, Zn, Fe and Mn using the same methods as those used in the analysis of foliar samples (Ch. 3, para. 3.2). Resources were not available for the analysis of C, B, Al or lignin. Litter pH was measured on 159 milled samples in a 1:10 suspension in distilled water, allowed to soak overnight (Lamb and Florence, 1975). The suspension was then stirred and allowed to settle for ten minutes. The electrode was placed in the surpernatant liquid, taking care to avoid contact with litter.

Regression analysis

From Table 4.1 it is apparent that factors influencing litter decomposition may be broadly grouped into three classes, viz. site factors, stand factors and the properties of the litter. Consequently, in an effort to understand the relationship between these factors and the decomposition of *P.patula* litter, models were constructed for the prediction of litter thickness from (1) site factors (2) stand factors (3) site plus stand factors (4) foliar nutrients (5) litter properties. The regression methods used were those described in Chapter 2.

4.3 RESULTS

4.3.1 SUMMARY STATISTICS

Litter layers in stands of *P.taeda* and *P.elliottii*, the other two main pine species in the study area, were also surveyed. From Table 4.2 it is apparent that *P.patula* litter was of greater and more variable thickness than the other two species. Some idea of the extent of thick litter layers can be conveyed by the fact that litter over 15 cm in thickness occurred on nearly a quarter of the sites sampled. These sites were specifically chosen to be representative of the study area as a whole.

Table 4.2 Summary statistics for *litter thickness* (cm) in stands of *P.patula*, *P.taeda* and *P.elliottii* in the Eastern Transvaal.

Species	No. of sites	Mean	Range	Std.dev.	C.V. %
P. patula	159	10,40	3 - 35	6,61	63,6
P. taeda	136	6,08	3 - 13	2,46	40,5
P. elliottii	144	4,92	3 - 14	1,95	39,6

4.3.2 LITTER THICKNESS AND SITE FACTORS

Correlation coefficients for *P. patula litter thickness* and important site factors are shown in Table 4.3. The site factors are arranged in descending order of magnitude of their correlation coefficients, which indicate their potential for inclusion in a model. Correlation coefficients were slightly higher than those for *site index* and site variables (Chapter 2, Tables 2.6 and 2.13).

During regression analysis, a study of *depth to stone layer* showed that stone layers with 40% or more stones were critical, as in the case of their relationship with *site index*. Scatter diagrams and residual plots revealed several non-linear relationships. In addition the plot of residuals versus predicted values showed the typical cone-shaped spread of points indicating heteroscedascity (Appendix 12). The outlier test indicated two outliers and several sites with large residuals. However, a logarithmic transformation of the dependent variable (*litter thickness*) cleared up all these problems, obviating the need for transformation of any independent variables, with the

Table 4.3 Correlation coefficients > 0,30 between *P. patula litter thickness* and site factors

No.	Variable	r
X_4	*Altitude*	0,65
X_3	*Rainfall*	0,56
X_{87}	*Exchange acidity*, A hor.	0,54
X_{36}	*Effective rooting* depth	-0,53
X_{86}	*pH, (H_2O) A hor.*	-0,52
X_{42}	*Weathering*	-0,52
X_{41}	*Timeball*	-0,51
X_{21}	*Thickness of solum*	-0,46
X_{20}	*Thickness of B hor.*	-0,45
X_{39}	*Vol. of stones, B hor.*	0,45
X_{73}	*Aluminium, A hor.*	0,42
X84	*Organic carbon, A hor.*	0,42
X40	*Vol. of stones, solum*	0,41
X_{41}	*Dolomite*	-0,40
X_{65}	*Bulk density, surface*	-0,39
X_{89}	*pH, (H_2O) B hor.*	-0,34
X_{71}	*Calcium, A hor.*	-0,30
X_{66}	*Bulk density, sub surface*	-0,30

(All correlation coefficients significant at the 0,0001 level).

exception of *effective rooting depth* (log), and reducing the size of the residuals to the extent that there were no outliers among sites. Tests showed no serious multicollinearity. The regression coefficients for the site factor model (Model 4.1) are shown in Table 4.4.

Table 4.4 MODEL 4.1: Regression coefficients to predict log *litter thickness* from site factors

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Altitude	0,00031	<0,01	0,29	3,79	0,00022
Exch acidity, A hor.	0,05453	0,02	0,20	3,24	0,00147
Coarse sand, B hor.	0,00586	0,08	0,20	2,58	0,01103
Dolomite	-0,12387	0,04	-0,20	3,52	0,00058
Coarse sand, A hor.	-0,00580	<0,01	-0,19	2,42	0,01686
ERD (log)	-0,11494	0,04	-0,18	3,11	0,00223
Rainfall	0,00016	<0,01	0,16	2,69	0,00801
Hue, B hor. (3,75 YR)	0,19497	0,07	0,14	2,96	0,00359
Clay, B hor.	-0,00260	<0,01	-0,13	2,32	0,02175
P, A hor.	-0,00869	<0,01	-0,12	2,38	0,01839
Hue, B hor. (1,25 YR)	0,26176	0,11	0,11	2,30	0,02306
Intercept	0,53890	0,19			

R^2 = 0,6784 S.E. = 0,155

A relationship between *litter thickness* and site factors has therefore been established. However, the role of *exchange acidity* in Model 4.1 is uncertain. It is possible that the acidity of the topsoil could be influenced by the thickness of the litter rather than the reverse, in which case variables such as *exchange acidity* and *pH* of the topsoil should not be classed as predictors. Omitting these variables from regression analysis resulted in a different model (Table 4.5).

4.3.3 LITTER THICKNESS AND STAND FACTORS

Correlation coefficients between *litter thickness* and selected stand factors are shown in Table 4.6.

Table 4.5 MODEL 4.2: Regression coefficients to predict log *litter thickness* from site factors, excluding soil acidity variables

X		Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Altitude		0,00035	<0,01	0,32	4,40	0,00002
Coarse sand, B hor.		0,00755	<0,01	0,26	3,31	0,00116
Dolomite		-0,14527	0,03	-0,23	4,26	0,00004
ERD (log)		-0,14174	0,04	-0,22	3,83	0,00019
Coarse sand, A hor.		-0,00571	<0,01	-0,19	2,33	0,02130
Rainfall		0,00014	<0,01	0,14	2,18	0,03058
Hue, B hor:						
	10R	-0,07320	0,03	-0,14	2,43	0,01619
	2, 5YR	-0,13028	0,05	-0,14	2,45	0,01562
	3,75YR	0,14050	0,07	0,10	2,05	0,04235
	10YR	0,00000	(ref. cat.)			
Intercept		0,53836	0,17			
R^2 = 0,6565			S.E. = 0,159			

Table 4.6 Correlation coefficients between *P. patula litter thickness* and stand factors

No.	Stand factors	r
Y_1	*Site index*	-0,70***
X_{105}	*Present top height*	-0,63***
X_{104}	*Mean D.B.H.*	-0,32***
X_{102}	*Stems per hectare (present)*	0,18*
X_{109}	*Total basal area*	-0,15
X_{110}	*Mean basal area*	-0,33***
X_{101}	*Age of stand*	0,10

(* = significant at the 0,01 level)
(*** = " " " 0,0001 ")

A log transformation of *litter depth* once again proved necessary in the regression analysis. The model comprising the variables selected by best-subsets regression had a coefficient of determination of 0,5744 but was highly multicollinear. Dropping of variables one at a time in an attempt to reduce the multicollinearity resulted in a model with only one variable, viz. *site index*, with a coefficient of determination of 0,5286. This value is only slightly lower than that for the full model (0,5744), and indicates that the only stand factor of real importance was *site index*.

4.3.4 LITTER THICKNESS AND SITE PLUS STAND FACTORS COMBINED

Correlation coefficients were as for those in Tables 4.3 and 4.4. When site and stand factors were combined in one regression model, multicollinearity tests showed that the coefficients were unstable and that ridge regression was necessary. The R^2 for the ridge model was 0,7448. However, when all the stand factors which were measured at present age (*DBH, total basal area, mean basal area*) were dropped and the regression analysis re-run, the resulting model had very stable coefficients (lowest eigenvalue 0,20756) and ridge regression was unnecessary. The R^2 was 0,7313, only very slightly lower than in the first case. The coefficients for this model (Model 4.3) are shown in Table 4.7.

Table 4.7 MODEL 4.3: Regression coefficients to predict log *litter thickness* from site plus stand factors

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Site index	-0,02757	<0,01	-0,42	7,43	<0,00001
Altitude	0,00037	<0,01	0,34	5,55	<0,00001
Exch. acidity, A hor.	0,06658	0,02	0,25	3,66	0,00035
Coarse sand, B hor.	0,00529	<0,01	0,18	3,65	0,00036
Age of stand	0,00805	<0,01	0,16	3,44	0,00077
Dolomite	-0,09287	0,03	-0,15	2,71	0,00755
Hue, B hor.					
1,25YR	0,25933	0,10	0,11	2,53	0,01260
3,75YR	0,18002	0,06	0,13	3,04	0,00276
10YR	0,00000	(ref. cat.)			
Exch. acidity, B hor.	-0,04727	0,02	-0,12	2,02	0,04515
Intercept	0,63116	0,19			

R^2 = 0,7313 S.E. = 0,140

It is apparent that a fairly good prediction of log litter depth (R^2 = 0,73) can be obtained from a combination of site and stand factors, the most important of which are *site index*, *altitude*, and *A horizon exchange acidity*. Most of the variables appearing in Model 4.3 are similar to those in Model 4.1 (site factors), plus the stand factors *site index* and *age*.

Exclusion of soil acidity variables from Model 4.3 for the same reason as in the case of Model 4.1 resulted in their replacement by the variable *rainfall* (Model 4.4, Table 4.8). *Age of stand* has been dropped from Model 4.3 and *Dolomite* (negative) replaced with *Timeball* (positive). *Altitude* has decreased in importance. The R^2 of this new model was only slightly lower than that of Model 4.3.

Table 4.8 MODEL 4.4: Regression coefficients to predict log *litter thickness* from site plus stand factors, excluding soil acidity variables

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Site index	-0,03030	<0,01	-0,46	8,23	<0,00001
Rainfall	0,00024	<0,01	0,24	4,09	0,00007
Coarse sand, B hor.	0,00587	<0,01	0,20	4,20	0,00005
Altitude	0,00021	<0,01	0,19	2,43	0,01637
Timeball	0,10263	0,03	0,18	3,05	0,00275
Hue, B hor:					
1,25YR	0,27296	0,11	0,12	2,60	0,01029
3,75YR	0,19061	0,06	0,14	3,13	0,00209
10YR	0,00000	(ref. cat.)			
Intercept	0,90603	0,17			
R^2 = 0,7112		S.E. = 0,145			

4.3.5 LITTER THICKNESS AND FOLIAR NUTRIENT CONCENTRATIONS

Correlation coefficients between *litter thickness* and foliar nutrient concentrations (dry mass) are shown in Table 4.9.

Table 4.9 Correlation coefficients between *P.patula litter thickness* and foliar nutrient concentrations

Foliar nutrients	r	Foliar nutrients	r
N	0,19*	*Cu*	-0,03
P	0,24**	*Fe*	-0,15
K	-0,11*	*Mn*	-0,24**
Ca	-0,60***	*Zn*	-0,04
Mg	-0,16*	*B*	0,31***
Na	0,34***	*Al*	0,15
S	0,14*		

* significant at 0,05 level
** " " 0,01 "
*** " " 0,0001 "

With the exception of *Ca*, correlations were generally low. A log transformation of the dependent variable was again necessary for building the model. Regression coefficients are shown in Table 4.10 (Model 4.5).

Table 4.10 MODEL 4.5: Regression coefficients to predict log *litter thickness* from foliar nutrient concenrations

X	Regress. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Ca	-1,97281	0,16	-0,81	12,36	<0,00001
B	0,01190	<0,01	0,28	5,01	<0,00001
Mg	1,44183	0,40	0,23	3,63	0,00039
Al	0,00036	<0,01	0,23	3,94	0,00013
Zn	0,00648	<0,01	0,15	2,43	0,01638
Intercept	0,59893	0,11			
R^2 = 0,6176		S.E. = 0,167			

Sixty-two percent of the total variation in litter thickness can therefore be explained by foliar nutrient concentrations of the elements in the model. Of these, foliar *Ca* appears to have the strongest relationship with *litter thickness*. Even a model with *Ca* alone had a coefficient of determination of 0,46. High foliar *Ca* levels are associated with well-decomposed litter layers, whereas all the other elements in Model 4.5 appear to be positively related to litter thickness.

Comparison between Model 4.5 and Model 3.1 (prediction of *site index* from foliar nutrients) is of interest. Precisely the same foliar nutrient variables appear in each. The R^2's of the two models also differ only slightly (Model 4.5 : 0,6176 ; Model 3.1: 0,5957). As the variable *site index* has already been shown to have a strong relationship with *litter thickness* (Model 4.4), it is possible that the influence of foliar nutrients on *litter thickness* is an indirect one via their influence on *site index* rather than a direct one.

4.3.6 LITTER THICKNESS AND ANALYTICAL PROPERTIES

4.3.6.1 Summary statistics

Results of laboratory analyses of litter properties are summarized in Table 4.11.

Table 4.11 Summary statistics for litter analytical properties

Litter property	Units	Mean	Range	Std dev.	C.V.%
pH	-	3,45	2,25 - 5,15	0,77	22,3
N	%	1,28	0,9 - 1,6	0,16	12,3
P	"	0,16	0,14 - 0,18	0,014	8,8
K	"	0,10	0,04 - 0,22	0,048	48,0
Ca	"	0,28	0,06 - 1,00	0,217	77,5
Mg	"	0,08	0,02 - 0,26	0,053	66,3
Na	"	0,06	0,04 - 0,10	0,012	20,0
S	"	0,13	0,06 - 0,28	0,033	25,4
Zn	mg kg^{-1}	15	5 - 42	8,69	57,9
Fe	"	4262	420 - 17600	3899	91,5
Mn	"	1083	15 - 9000	1787	165,0
(n = 55)					

The minimum value for litter *pH* (2,25) is lower than the probable minimum of 3,0 quoted by Baule and Fricker (1970, p 24) and Pritchett (1979, p 67). The mean value for *N* is lower than average values for N in mor in Europe (1,4-

1,9%) (Baule and Fricker, 1970, p 25).

The mean values of Table 4.11 are in general agreement with those of Morris (1986) and Lundgren (1978) for *P. patula* litter in Swaziland and Tanzania, respectively (only macro elements were analysed by these workers). Litter *P*, however, was much higher in the Eastern Transvaal than in either Swaziland or Tanzania, whereas *Ca* and *Mg* were much higher in Tanzania than in the Eastern Transvaal and Swaziland.

4.3.6.2 Nutrient accumulation in litter

Using the mean values from Table 4.11, the mean value for *litter thickness* (Table 4.2) and the regression equation of Schutz *et al* (1983) for conversion of *litter thickness* to *litter mass*, it is possible to determine the mass of nutrients per hectare of *P. patula* litter of mean thickness. This is shown for some of the macro-nutrients in Table 4.12. Also shown is the mass per hectare of nutrients for the thickest litter layer sampled (35 cm, plot no. P30). The actual litter analyses for this particular site were used in the calculation. For comparison, topsoil nutrient pools were calculated for available P and exchangeable K, Ca, Mg using the formula

$$NC / 100 \times BD \times D$$

where NC = A 1 horizon nutrient concentration in mg kg^{-1}
BD = " " bulk density in kg m^{-3}
D = " " depth in m.

Table 4.12 Mass per hectare of nutrients in litter layers of (A) mean and (B) maximum thickness, compared with topsoil nutrient pools

	A		B	
	Litter	Topsoil	Litter	Topsoil
Thickness (cm)	10,4	18,8	35	15
Mass ha^{-1} (t)	82	-	272	-
N ha^{-1} (kg)	1045	-	2994	-
P " "	130	9	381	2
K " "	82	54	218	15
Ca " "	229	62	272	2
Mg " "	65	27	54	7

It is evident that litter layers contain large amounts of nutrients, particularly of *N*. Even on a site with a litter layer of average thickness, the mass of nutrients in the litter exceeds that in the underlying topsoil, particularly in the case of *P* and *Ca*. Differences appear to be greatly accentuated on sites with thick litter layers, even allowing for a possible underestimate of *bulk density* (Ch. 2, para. 2.3.2).

4.3.6.3 **Interrelationships**

Correlation coefficients among litter variables were generally high (Table 4.13). Litter *pH* was correlated with several nutrients, but especially with *Ca* and *Mg*, which in turn were highly correlated with each other. Expressed in a different way, *pH*, *Ca* and *Mg* vary concurrently regardless of litter thickness.

Table 4.13 Correlation coefficients >0,5 for relationships among litter analytical properties

litter properties	r	litter properties	r
pH - *K*	0,54	*K* - *Zn*	0,66
- *Ca*	0,85	*Ca* - *Mg*	0,83
- *Mg*	0,86	*Mg* - *Zn*	0,73
- *Zn*	0,79	*S* - *Fe*	0,78
- *Mn*	0,67	*Zn* - *Fe*	0,56
P - *Zn*	0,53	- *Mn*	0,61
K - *Mg*	0,62		

(all correlation coefficients significant at 0,0001 level)

It is also of interest that *Zn* appeared to be correlated with all properties except *N* and *S*. Whether this is of any importance is not known. PCA and factor analysis generally confirmed the strong dependencies among litter analytical properties. In PCA the first three components accounted for 75% of the total variation, with the first component alone accounting for 44% (Table 4.14). Variables associated with the first component were *pH*, *Mg* and *Zn*, with the second *S* and *Fe*, and with the third *N* and *Na*. These groupings are not easily explained.

Table 4.14 Principal components analysis of litter analytical properties

Principal component	Eigenvalue	Difference	Proportion of variation (%)	Cumulative variation (%)
1	4,82	2,92	43,8	43,8
2	1,90	0,42	17,2	61,1
3	1,48	0,62	13,4	74,5

4.3.6.4 Litter and soil analytical properties

Some litter properties were correlated with soil properties. These are shown in Table 4.15. Litter *pH* was moderately correlated with soil *pH*, soil *Ca* and *Mg*, and soil *exchange acidity*. Only *Ca* in litter and soil were highly correlated, but soil *Ca* was also highly correlated with litter *Mg*. Litter *Ca* and *Mg* were moderately correlated with soil *Mg*, *organic carbon*, *pH* and *exchange acidity*.

Table 4.15 Correlation coefficients between selected litter and soil analytical properties (A 1 horizon)

Litter	Soil						
	P	*K*	*Ca*	*Mg*	*Org.C*	*pH (H_2O)*	*Exch.Ac.*
P	0,04	0,37	0,31	0,35	-0,19	0,10	-0,16
K	<0,01	0,47	0,32	0,32	-0,25	0,14	-0,19
Ca	<0,01	0,62	0,78	0,66	-0,53	0,62	-0,60
Mg	-0,02	0,58	0,72	0,56	-0,50	0,53	-0,58
pH	0,12	0,46	0,54	0,51	-0,47	0,59	-0,55

Significant at 0,0001 level: r >0,62
" " 0,001 " " "0,41
" " 0,01 " " "0,35

4.3.6.5 Litter and foliar nutrients

It is of interest to compare litter mean values (Table 4.11) with foliar mean values (Table 3.1). These comparisons and correlations are shown in Table 4.16.

Table 4.16 Mean values and correlation coefficients for litter and foliar nutrients

Nutrient	Units	Mean values Litter	Foliar	Correlation (r)
N	%	1,28	2,15	0,05
P	"	0,16	0,18	-0,05
K	"	0,10	0,87	0,18
Ca	"	0,28	0,26	0,76 ***
Mg	"	0,08	0,17	0,06
Na	"	0,06	0,03	0,07
S	"	0,13	0,16	0,22
Zn	mg kg^{-1}	15	25	0,13
Fe	"	4262	113	0,09
Mn	"	1083	1308	0,52 ***

(** significant at 0,0001 level)

The mean values for litter and foliar *P*, *Ca*, *Na*, *S* and *Mn* did not differ greatly, whereas those for *N*, *K*, *Mg* and *Zn* were lower for litter than for foliar elements. The largest reduction by far in nutrient concentration between leaves and litter was in the case of K. Morris (1986) also found that K was not strongly retained in the litter. These lower values could be due either to internal translocation before litterfall or to more rapid leaching from the litter. The large difference in *Fe* mean values for litter and needles is difficult to explain. The high correlation between foliar and litter *Ca* suggests that it is not readily translocated before litterfall (Pritchett, 1979 p.207). Apart from *Mn*, correlations for all other nutrients were low.

Had the L, F and H classification been used it could have been possible to gain a better insight into the nutrient cycling process. The 01 and 02 classification does not make provision for the separate study of freshly fallen litter.

4.3.6.6 **Litter properties and litter thickness**

Correlations between litter properties and litter thickness are shown in Table 4.17. The highest correlations were for *pH*, *Mg* and *Ca*. As in all previous regression analyses with *litter thickness*, its log transformation

Table 4.17 Correlation coefficients between litter analytical properties and *litter thickness*.

Litter properties	r
pH	-0,73 ***
N	-0,16
P	-0,34 **
K	-0,34 **
Ca	-0,56 ***
Mg	-0,65 ***
Na	0,00
S	-0,23
Zn	-0,15
Fe	-0,19
Mn	-0,17

(** significant at 0,01 level)
(*** " " 0,0001 ")

again proved necessary when modelling the effect of litter properties. The regression coefficients for the model are shown in Table 4.18 (Model 4.6). The *Cp* criterion indicated that subsets with four and five variables were also acceptable, by addition of *Ca* and *Mn*, but these variables were non-significant, increased multicollinearity and only slightly increased the coefficient of determination. Dropping *pH* from the model to determine the effect of litter nutrients alone resulted in a model with two variables, *Mg* and *Zn*, with R^2 = 0,5916. pH was clearly the most important variable in Model 4.6. In fact, the R^2 for a model with *pH* alone was not much lower than that for the full model, viz. 0,6074.

Table 4.18 MODEL 4.6: Regression coefficients for the model to predict log *litter thickness* from litter properties

X	Regression Coefficient	S.D.	Stdd coeff.	t-value	Probability
pH	-0,18981	0,06	-0,53	3,30	0,00179
Mg	-1,61324	0,82	-0,32	1,97	0,05381
N	-0,26225	0,14	-0,16	1,88	0,06595
Intercept	2,07166	0,24			
R^2 = 0,6572		S.E. = 0,171			

4.3.7 ROOTING WITHIN THE LITTER

The correlation coefficient between *litter thickness* and the volume of rooting in the litter was found to be r = 0,82, confirming that thicker layers had greater root colonization. This always occurred in the lower part of the litter layer, i.e. in the F and H layers.

In mature *Abies amabilis* stands in Washington state Vogt *et al* (1983) found that the biomass of conifer roots in the litter was significantly higher than in the mineral horizons. Although this was not physically measured in the Eastern Transvaal, it could be seen to be the case with the naked eye on many thick litter sites. There have been few studies of rooting within litter, a notable exception being the work of Vogt *et al* (1983). They offer several explanations for the increased localization of roots in the forest floor: (1) increased rooting space becomes available as organic matter accumulates, (2) roots respond to nutrient deficiencies in the mineral horizon caused by increased nutrient immobilization in the detritus, (3) reduction in available O_2 occurs with increasing depths, (4) Fe and Al toxicity inhibits root growth in the mineral horizons, and (5) mineral soil temperatures are reduced. Not mentioned by Vogt *et al* is the further possibility that moisture conditions may sometimes be more favourable in the litter than in the topsoil, thus affecting root distribution.

4.4 DISCUSSION

The first question arising from the results of this study is whether the possible causes of excessive litter accumulation have been identified. A substantial percentage of the total variation in *litter thickness* was accounted for by the variables in Models 4.1 to 4.6, in spite of the sampling problems described in para. 4.2. Although the predictors are related to the dependent variable statistically, they do nevertheless provide clues to the possible reasons for the accumulation of undecomposed litter on so many sites. Taken as a whole, the model predictors discussed in para. 4.4.1 below are thought to act indirectly by promoting or retarding the activities of micro-organisms responsible for decomposing litter.

A second question relates to the effects of litter accumulation. Some of the important beneficial roles of litter were described in the first paragraph of this chapter. The evidence from this study that these beneficial roles can be reversed into potentially harmful effects when accumulation exceeds decomposition, requires examination, however. This is discussed in para. 4.4.2 below.

4.4.1 FACTORS ASSOCIATED WITH VARIATION IN LITTER THICKNESS

4.4.1.1 Site factors

Rainfall

The positive regression coefficient for *rainfall* in Models 4.1, 4.2 and 4.3 indicates that litter decomposition may be retarded by increasing rainfall. It is possible that high rainfall reduces aeration of the litter to the extent that biological processes are inhibited. Site wetness has been cited as a factor contributing to litter accumulation (Olson, 1963; Pritchett, 1979, p 61).

Altitude

Litter layers were thicker at high altitude (Models 4.1 to 4.4). This is supported by evidence from Swaziland, where Morris (1986, p 128) found that *altitude* together with *stand age* accounted for 89,5% of the variation in litter mass in unthinned stands of *P.patula*. As in the case of the site index models (Chapter 2), *altitude* is thought to be a surrogate of temperature, with lower temperatures inhibiting biological processes. However, as Bevan (1985) points out, litter breakdown in conifer forests at intermediate latitudes in the northern hemisphere seems to occur throughout all seasons and at temperatures well below those along the eastern escarpment of southern Africa. It is probable that temperature is a critical factor only in combination with the other site, stand and litter factors.

Geology

Dolomite appeared as a category of *geology* in Models 4.1, 4.2 and 4.3 with a negative coefficient, indicating that litter was well-decomposed on soils derived from this substrate. The fact that *dolomite* was the only category of *geology* to be included in these models could be assumed to indicate that litter layers were the thinnest on soils of *dolomite*. Conversely the positive coefficient of *Timeball* in Model 4.4, also the only category of *geology* to be included, could indicate that litter layers were thickest on soils of this substrate. This fact was generally confirmed by observation in the field.

Effective *rooting depth*

Litter decomposition appeared to be more rapid on deeper soils (Models 4.1, 4.2), agreeing with the findings of Florence and Lamb (1974). While deeper soils generally have a moist micro-climate able to sustain the activity of micro-organisms, shallow soils may be too dry to promote decomposition (Baule and Fricker, 1970, p 23). The fact that *ERD* did not appear in Models 4.3 and 4.4 could probably be ascribed to the presence of the variable *Timeball*, which develops the shallowest topsoils (Table 1.10).

Subsoil colour

Of six *Hue B* categories expressed in dummy variable format, two were selected by best-subsets regression, viz. *1,25YR and 3,75YR* (Models 4.1, 4.3, 4.4) as differing from the reference category (10YR). As *1,25YR* is represented by only two sites and *3,75YR* by six sites, replication can hardly be regarded as sufficient. But when *Hue B* was dropped from the models due to this uncertainty and regression analysis re-run, the new models had much lower coefficients of determination and lower significance levels for the remaining variables. It is therefore apparent that a relationship between *litter thickness* and B horizon *hue* exists, in spite of a lack of replication. Whereas in Model 4.1 only two categories were included, Model 4.2 comprised three categories, indicating a stronger relationship. Although all categories of *Hue B* were not included in models, the signs of the correlation coefficients for all categories of *Hue B* assist in explaining the relationship (Table 4.19).

Table 4.19 Correlation coefficients between log *litter thickness* and categories of *Hue, B horizon*

Hue B	r
10 R	-0,33
1,25 YR	-0,01
2,5 YR	-0,29
3,75 YR	+0,10
5 YR	+0,24
7,5 YR	+0,20
10 YR	ref.cat.

The change in sign from negative for the first three categories to positive for the second three, implies that litter thickness increases as the hue of the B horizon changes from red to yellow. As yellowing subsoil indicates increasing wetness, this trend can be assumed to confirm the effect of the variable *rainfall*, viz. that wet soil conditions are associated with an increase in litter thickness. This is in agreement with a review of literature on tree species in Europe (Baule and Fricker, 1970, p 23).

Soil texture

The negative regression coefficient for *coarse sand* content of the A horizon (Models 4.1, 4.2) shows that litter thickness decreased with increasing coarse sand. This could be a drainage factor, surface soils high in coarse sand being better drained and thus better aerated. *B horizon coarse sand* on the other hand was positively related to *litter thickness* (Models 4.1 to 4.4). B horizons high in coarse sand generally indicate poor sites with low nutrient status and poor drainage, e.g. soils on Black Reef. The negative relationship between *litter thickness* and *clay content* (Model 4.1) is probably complementary to that of *B horizon coarse sand*. Pritchett (1979, p 62) reports greater accumulation on fine-textured soils, but Florence and Lamb (1974) quote work indicating the opposite.

Soil nutrients

A horizon *P* was the only nutrient to be included in a model, and only in Model 4.1. The negative relationship between *litter thickness* and *P* levels in the surface soil could be ascribed to the more favourable environment for microbial activity to be found in more fertile soils. This agrees with findings elsewhere quoted by Pritchett (1979, p 61).

Site index

Site index was the most important variable in Model 4.3, and by far the most important in Model 4.4. This implies that the activity of micro-organisms responsible for decomposition of litter is most strongly dependent on favourable environmental conditions. Although *site index* was at first classified as a stand variable (para. 4.3.4), it probably acts as a surrogate for many of the variables in the models described in Chapter 2.

A problem requiring attention is the apparent contrasting findings in the literature (Table 4.1) regarding the positive or negative relationship between *litter thickness* and *site index*. Model 4.4 shows that the relationship for *P.patula* is inverse. Work by the author has shown that the same is true for *P.elliottii* and *P.taeda* within the study area. In the Cape Province, however, the relationship is positive for pine species, including *P.elliottii* (de Ronde, 1988, p 69). An explanation is not apparent.

4.4.1.2 Stand factors

Age of stand

The only stand factor to be included in a model was *age*. As it appeared only in Model 4.3, it was evidently not strongly related to *litter thickness*. In *P.radiata* stands in South Australia, litter accumulation increased up to a stand age of 20 years and became stabilised in older stands (Florence and Lamb, 1974). A similar trend is reported in a review of the literature by Armson (1977, p 67) and Lundgren (1978, p 163). On the other hand, Morris (1986, p 128) found *stand age* to be a key predictor of *litter mass* of *P.patula* in Swaziland. His model contained the two variables *age* and *altitude* (R^2 = 0,895). In this case the importance of *age* can be ascribed to the wide range in age of the 24 stands sampled, from as young as 8 years, to 34 years.

Stand density

The non-appearance of *stems per hectare* in any of the models, in spite of wide differences in stocking, confirms the findings of Schutz *et al* (1983) that this variable is not related to litter thickness in stands with closed canopies.

Litterfall

Litterfall rates may vary according to site (Pritchett, 1979; Singh 1982), but no information on *P.patula* in southern Africa is available.

4.4.1.3 Litter properties

Of the litter properties studied, only *pH, Mg* and *Zn* appeared in a model (Model 4.6). If, however, *pH* is assumed to be an effect rather than a cause of thick litter layers and disregarded, the model then contains the two variables *Mg* and *Zn* (R^2 = 0,59). However, as PCA (Table 4.14) indicated strong dependencies among litter nutrients, *Mg* and *Zn* are not necessarily the only nutrients of importance. *Mg*, for example, was correlated with *Ca* (r = 0,83) (Table 4.13), and *Ca* could therefore be as important as *Mg*. These variables were inversely related to *litter thickness*. This is in line with findings in the literature (Baule and Fricker, 1970, p 22).

As stated in para. 4.2, other litter properties of potential importance such as C/N ratio, lignin and others could not be studied. These have been found to influence decomposition in the literature (Table 4.1). Lundgren (1978, p 163) also cites polyphenol content as a factor in *P.radiata* litter. The waxy cuticle of needles was found to retard decomposition of *P.patula* in Natal (Higgs, 1981).

4.4.1.4 Roots and fungi

There is conflicting evidence on the role of roots and fungi in suppressing litter decomposition. Vogt *et al* (1983), found that slow forest floor turnover time was primarily the result of a greater input of roots and not above-ground litterfall inputs into detritus production. On the other hand Gadgil and Gadgil (1975, 1978) produced evidence to indicate that roots do not suppress decomposition of litter, but that the presence of external mycelia of mycorrhizal fungi do, and may be a major factor in the formation of raw humus. Dighton *et al* (1987) found that a mycorrhizal fungus encouraged decomposition, but that a saprotroph had the opposite effect.

4.4.2 EFFECTS OF LITTER ACCUMULATION

4.4.2.1 Increase in soil acidity

Variation in *litter thickness* was strongly associated with topsoil *exchange acidity* (Models 4.1, 4.3). In the construction of litter prediction models it was assumed that increased acidity was a result, rather than a cause, of litter accumulation (Models 4.2, 4.4). Although these is no conclusive proof available from the data to verify this assumption, it is nevertheless very likely that topsoil exchange acidity responds to variation in litter thickness. Comparing *pH* values for litter (Table 4.11) and topsoil (Table 2.2), it is evident that litter had a much lower mean *pH* (H_2O), viz. 3,45 as against 4,60 for topsoil. The minimum value for litter *pH* (2,25) was also much lower than the minimum for topsoil (4.0). It may therefore be reasonable to assume that the organic acids released from the litter could have a lower *pH* than the topsoil by the time they have percolated through to the mineral soil, thus increasing soil acidity gradually. This view was also expressed by Baule and Fricker (1970) in reviewing work on litter in Europe. Comparing natural grassveld with adjacent first and second rotation stands of *P. patula* in Swaziland, Morris (1984) found an increase in soil *Al* and decrease in soil *pH* from grassveld to second rotation. As the forest floor mass increased by 37% from first to second rotation, the increase in soil acidity could have been due to litter accumulation.

Similarly there is uncertainty whether the drop in *pH* of litter associated with an increase in *litter thickness* (Model 4.6) is a result, or a cause, of litter accumulation. Either way, there may be important implications from the increased levels of atmospheric deposition of pollutants being experienced in the Eastern Transvaal Escarpment area (Tyson *et al*, 1988). If increased acidity is a result of litter accumulation, then this acidity could be expected to increase still further under acid rain conditions, with an aggravation of the effect on soil described above. If, on the other hand, an increase in litter acidity is a cause of litter accumulation, then acid rain could be expected to increase the thickness of litter layers still further. Under laboratory and simulated field conditions, Ineson and Wookey (1988) showed that high SO_2 concentrations commonly encountered caused a substantial drop in the pH of *Pinus nigra* litter with enhanced leaching of cations, especially Ca and Mg.

4.4.2.2 Immobilization of nutrients

From Table 4.12 it is evident that large amounts of nutrients accumulate in the litter, and that these amounts appear to greatly exceed the available nutrients in the topsoil as litter layers increase in thickness. The vital question is whether the nutrients in the litter are available for tree growth or not. If available, then thick litter layers may not be harmful, and possibly even beneficial on poor sites. On the other hand, if nutrients are immobilized, then thick litter layers represent a potential threat to continued forest productivity.

Morris (1986, p 276) believed that the "lock-up" of N, P, Ca and Mg in thick litter layers of *P.patula* in Swaziland represented a larger drain upon nutrients moving in the internal cycle than export from the site in log removal and slash burning. This he regards as the most extensive threat to long term productivity in the Usutu Forest. The generally thicker layers in the Eastern Transvaal would therefore be a cause for concern. However, the extensive root colonization of the litter (para. 4.3.7) implies that nutrients cannot be entirely locked up as suggested by Morris (1986), but that some mobilization must be taking place. Morris makes no reference to rooting in the litter, yet this is clearly a factor that needs to be taken into consideration in nutrient cycling.

Few studies appear to have dealt with the degree of immobilization of nutrients in the litter layer. A figure of 55% of N is quoted by Lundgren (1978, p 163) from work on *P.radiata* litter in Australia. Baule and Fricker (1970, p 24) quote 98% for N, 84% for P, 20% for K and 91% for Ca for mor layers in Europe.

4.4.2.3 Other effects

The problems of access, fire hazard and lack of wind-firmness caused by thick litter accumulation have already been stressed. In addition such sites have been found to cause regeneration problems. When holes are dug through the litter in preparation for planting in the mineral soil, the microclimatic environment becomes unfavourable. Extremes in temperature are accentuated, resulting in severe tree mortality despite repeated blanking, e.g. on Ceylon S.F.

4.5 CONCLUSIONS

4.5.1 CHARACTERISTICS OF LITTER LAYERS

1. Litter layers were found to be thicker and more variable under stands of *P.patula* than under *P.taeda* or *P.elliottii*. Litter was thicker than 15 cm on nearly 25% of the 159 sites sampled.

2. The heterogeneity of the forest floor and the penetration thereof by fine roots present difficult sampling problems. The volume of tree roots in the litter was correlated with the thickness of the litter.

3. The South African binomial soil classification system was found to be inadequate in its classification of litter layers in forestry. The L, F and H system is preferable.

4. Litter *pH* was lower than in other parts of the world, and considerably lower than the pH of topsoil. *N* concentrations were lower than in mor layers in Europe. Comparing *P.patula* litter in the Eastern Transvaal, Swaziland and East Africa, *P* concentrations were much higher in the Eastern Transvaal, while *Ca* and *Mg* were lower than in East Africa.

5. Large amounts of nutrients can accumulate in the litter. Up to 3 t ha^{-1} of N were recorded. The mass of nutrients in litter of average thickness exceeds that of the topsoil, especially in the case of P, Ca and probably N. Differences widen as litter thickness increases.

6. PCA and correlation coefficients indicated high degrees of association among litter nutrients.

7. Litter *N*, *K*, *Mg* and *Zn* concentrations and especially *K*, were lower than foliar concentrations of these elements. This could be due either to internal translocation before litterfall, or to rapid leaching from the litter.

8. *Calcium* has once again featured prominently in this study. The highest correlation coefficient between soil and foliar nutrients (Ch. 3, Table 3.6) was for *Ca* ($r = 0,50$), suggesting that Ca is readily taken up by the needles. The highest correlation coefficient between foliar and litter nutrients was also for *Ca* ($r = 0,76$), indicating that Ca is not readily

translocated before litter fall. The highest correlation coefficient between litter and soil nutrients was for *Ca* (r = 0,78), but the reason for this is not known.

4.5.2 FACTORS ASSOCIATED WITH VARIATION IN LITTER THICKNESS

1. The environmental factors and properties of the litter itself which influence the thickness of the litter layer are thought to do so indirectly by promoting or retarding the activities of micro-organisms responsible for decomposing litter.

2. Some of the environmental factors associated with variation in *litter thickness* were identified by means of regression models which accounted for up to 71% of the variation. Although the variables in the models cannot be interpreted as causal, they do provide clues as to the reasons for variation in litter thickness. Model 4.4 (Table 4.8) is recommended for prediction purposes. In all cases a logarithmic transformation of the dependent variable (*litter thickness*) was required.

3. The major environmental factors associated with variation in litter thickness were found to be, in order of importance:

   Site index
   Litter thickness was inversely related to *site index*, by far the most important variable in the models.

   Altitude
   Litter thickness increased at higher altitude, where cooler temperatures appear to limit decomposition.

   Soil wetness
   Wet soil conditions retarded decomposition of litter. This was expressed by variables such as *rainfall*, *soil colour hue* and *soil texture*. Litter decomposition was equally retarded on shallow soils, where conditions are too dry for micro-organism activity.

   Geology
   Litter accumulation was greatest on soils derived from the Timeball Hill Formation (dryness, high altitude) and least on dolomite-derived soils (high site index, deep soils).

4. *Stand age* was not strongly related to *litter thickness* as the sites sampled were in stands with closed canopies. The absence of *stems per hectare* from any models confirmed earlier work by the writer that *litter thickness* was not related to *stand density* after canopy closure.

5. The association between litter nutrients and decomposition was obscured by dependencies among the variables.

6. A model with foliar nutrient concentrations explained 62% of the variation in *litter thickness*, but it is thought to be an indirect effect as virtually the same nutrients appear in the model with *site index* as dependent variable.

7. The role of tree roots and mycorrhizal and other fungi in suppressing litter decomposition is not clear.

4.5.3 EFFECTS OF LITTER ACCUMULATION

1. *Litter thickness* was strongly related to topsoil *exchange acidity*. There was uncertainty whether this was a cause or an effect, but there was some evidence in support of the latter. This was not conclusive, however. Current levels of atmospheric pollution being experienced in the Eastern Transvaal can be expected to increase either the acidity or the accumulation of litter, or both.

2. Although large amounts of nutrients accumulate in the litter, the colonization of litter by pine roots could indicate that these nutrients are not entirely immobilized. The extent to which this might occur is uncertain.

3. In the light of the above, it is still uncertain to what extent thick litter layers may be a threat to the maintenance of site productivity.

4. Nevertheless, thick litter layers have been found to cause regeneration problems.

4.5.4 FURTHER RESEARCH

1. There is some urgency in the need to determine whether excessive

accumulation of litter is a threat to the maintenance of site productivity or not. This can be revealed by research on acidification processes in the litter and on nutrient cycling to determine the degree of nutrient immobilization in litter.

2. Should excessive litter accumulation prove harmful, the dividing line between the positive and negative roles of litter would need to be determined along with reasons for the change in these roles.

3. The relationship between *litter thickness* and variation in litterfall rates, as well as litter properties such as C/N ratio and lignin content, require attention.

4. Strategies to ensure representative sampling of the extremely variable litter layers require attention.

5. Research is necessary on the cumulative effects of atmospheric pollution on litter dynamics.

6. The observed phenomenon of *litter thickness* being inversely proportional to *site index* in the Transvaal but directly proportional to *site index* in the Cape, even for the same species, requires research.

CHAPTER 5

SITE-WOOD RELATIONSHIPS

Although a considerable amount of research in South Africa has been devoted to the influence of factors such as growth rate and age on wood properties, very little is known about the influence of environmental factors. Any important relationship of this kind would have economic implications. Productivity and species choice would be affected and there would be implications for tree improvement programmes. The study of site relationships for *P. patula* would thus be incomplete without consideration of wood properties. This has not previously been attempted for this species on any large scale.

Three important wood properties of *P.patula* were selected for study, viz. *density, spirality* and *stem bumps:*

Density is widely held by wood technologists to be the single most important wood variable, as it is closely correlated with timber strength, pulp yield and pulp quality (Cown, 1974).

Spirality is an important defect of *P.patula* causing warp, twist and loss of strength in sawtimber and veneer (Kromhout, 1966).

Stem bumps are of two types, viz. those associated with compression failure resulting from wind damage, and those associated usually with nodes and often referred to as nodal swellings, the cause of which is unknown. Wood properties most affected by stem bumps are modulus of rupture, fibre stress at proportional limit, and maximum crushing strength in compression parallel to the grain (Banks, 1956). There are also problems in the sawing of the timber (Tweefontein Timber Co., pers. comm), and the quality of veneer logs is adversely affected.

5.1 DENSITY

5.1.1 LITERATURE REVIEW

Density has been the most widely studied wood parameter as far as environmental effects are concerned, and there is a large volume of literature on the subject, often with conflicting findings.

Geoclimatic influences

Most studies have concentrated on the macro-scale influence of geographic location and climate, reviewed by Zobel *et al* (1960), Ledig *et al* (1975) and Tsoumis and Panagiotidis (1980).

An increase in density with decreasing latitude has been reported in many parts of the world. In the USA several species of the southern pines show an increase in density from north to south (Zobel *et al* 1960; Ledig *et al* 1975; Wahlgren and Schumann, 1975; Talbert and Jett, 1981) as do some hardwoods (Sluder, 1972). Many species in Europe show a similar trend (Tsoumis and Panagiotidis, 1980). In New Zealand outer wood density decreases with increasing latitude at a rate of about 10 kg m^{-3} per degree (Cown, 1974). A possible explanation for the effect of latitude is that the shorter the growing season (in higher latitudes), the less time there is for the production of photosynthate necessary for cell-wall thickening. This decrease in the amount of cell-wall substance results in a decrease in density (Ledig *et al*, 1975).

An inverse relationship between density and altitude (a temperature effect) has been reported for many species. The density of several of the southern pines in the USA increases from inland to the coast (Zobel *et al*, 1960; Ledig *et al*, 1975; Wahlgren and Schumann, 1975; Talbert and Jett, 1981), as is the case with *Liriodendron tulipifera* (Sluder, 1972). A similar trend has been reported for *P.caribaea* in Fiji (Cown, 1981) and for *P.radiata* in New Zealand, where outer wood density decreases by about 15 kg m^{-3} per 100 m increase in altitude (Cown, 1974). In South Africa small-scale comparisons for *P.elliottii*, *P. kesiya*, *P.taeda* and *P.caribaea* have confirmed this general trend (Scott and du Plessis, 1951; De Villiers, 1974; Van der Sijde, 1976; Boden, 1982; Wright *et al*, 1987a). However, for *P.oocarpa* and *P.patula* subsp. *tecunumanii*, density was found to be higher at a high altitude site (Eastern Transvaal) than at a low altitude site (Zululand coast) (Wright *et al*, 1987b).

An inverse relationship between density and rainfall has been found in the USA for some southern pines (Zobel *et al*, 1960; Wahlgren and Schumann, 1975), and in Costa Rica for *Cordia alliodora* (Howe, 1974).

Site quality influences

Fewer studies have been done on the more localized effects of site, and the results have often been conflicting (Zobel *et al*, 1960). Site quality in general ranges in its effect on density from negative, e.g. *Liriodendron* (Sluder, 1972), to positive, e.g. *P.nigra* (Tsoumis and Panagiotidis, 1980), to no effect, e.g. *Quercus rubra* (Hamilton, *et al*, 1978). Soil moisture parameters have been found to have some influence on density. Working with clonal material of *P. radiata*, Harris *et al* (1978) found that density was inversely related to moisture stress. There was a similar trend with soil moisture retention capacity in the case of *P.caribaea* (Cown, 1981). Other reported relationships were for soil parent material (Hamilton, *et al*, 1978) and for phosphorus deficiency, which resulted in higher density (Harris *et al*, 1978).

Studies in *P.patula*

The relationship between wood density of *P.patula* and environmental factors has not yet been intensively studied. Turnbull (1947) recommended that such studies be undertaken, after he had found that density gradient was influenced by site. In a study of six trees from each of six sites in Malawi, Burley (1973) found that less than 4% of the total variation in density was due to site differences. A later study in Malawi by Adlard *et al* (1979), using one tree from each of 62 sites, showed that the relationship between density and topographic position was very weak. Large differences in density were noted in South Africa by De Villiers (1974) in wood from the sub-tropics compared with wood from the cooler zones. In a review on *P.patula*, Wormald (1975) reported small differences due to geographic location or site. In a study on 20 trees from each of 12 sites in the Natal Midlands, Boden (1982) found that a regression model with tree height, DBH, bark thickness, altitude and latitude explained 30% of the total variation in density.

The studies reviewed above indicate that wood density of *P.patula* is, in broad terms, influenced by site, but due to an insufficient number either of sites, or of trees per site, conclusions regarding detailed or quantitative relationships have not been possible.

Genetic variation

A reason for the failure of so many studies to show meaningful relationships between density and site characteristics may be genetic variation. Most publications emphasize the magnitude of individual tree variation, which is often larger within than between sites. The subject has been reviewed by Zobel *et al* (1960) and Ledig *et al* (1975). It is common for differences among trees within stands to account for 50 to 60% of the variation in wood properties, and in the case of *P.rigida* up to 71% (Ledig *et al*, 1975). In site studies an adequate sample size is therefore essential if site variation is not to be overshadowed by genetic variation.

5.1.2 METHODS

Field Survey

The mean age of stands sampled during the survey to determine site-growth relationships was 38 years (Table 2.2). The range in ages was such that wood properties could be studied in samples with at least 30 rings, from 147 sites. The fact that the trees felled for sampling (Ch. 2, para. 2.4.2) were the ten largest per site had two advantages. (1) Any unknown source of variation possibly resulting from a wide range in D.B.H. would be reduced. (2) Tree dimensions would approximate those most likely to eventually result from the tree improvement programme.

A disc was removed at 3 m height. This is close to the 5% of tree height from which whole-tree mean density for *P.patula* can be reliably predicted (Adlard *et al*, 1979). Sampling was completed within a three-week period in winter. Rejection of samples due to defects and other problems resulted in a sample size of 8 trees, and in a few cases 7 trees, per site. The total number of trees sampled was 1146.

Laboratory determinations

From each disc a planed section 15 mm wide and 6 mm high was sawn across its diameter so as to include the pith, orientated at random. In eccentric cross-sections the strip was taken from the shortest axis so as to minimize the incidence of compression wood. Knots and other defects were avoided. Each strip was divided in two at the pith (sections A and B) and separated into samples containing rings 1 to 8 (1) and rings 23 to 30 (2). The following procedure was used to determine extracted wood density:

The samples were soaked in ethyl alcohol for 24 hours to remove moisture and then extracted in a benzene-alcohol (3:1) mixture in a soxhlet extractor for

30 cycles (6 hours). They were then soaked in alcohol for 4 hours, and washed in running water overnight. The samples were saturated with water for 12 hours. Mass was determined in water (X) and in air (Y). The mass of the chain used to suspend the samples in water was also determined (Z). The samples were then oven-dried at 90^{0} C for 40 hours, cooled in a dessicator for 2 hours and oven-dry mass determined (M). A correction factor for volumetric contraction had to be applied, using a previously determined factor (P), which is standard for the species. Extracted wood density in g cm^{-1} was calculated for each sample as follows:

$$\text{Density} = \frac{M}{Y - (X - Z)} \times \frac{100}{100 - P} \quad g\ cm^{-3}$$

A total of 4584 samples were thus analysed.

Density parameters

(1) *Inner density* per tree was obtained from rings 1 to 8, averaged for the two radial samples:

$$\textit{Inner density} = \frac{A1 + B1}{2} \quad g\ cm^{-3}$$

Rings 1 to 8 were selected as being the most suitable for comparing sites, as the first thinning in most stands rarely took place before 8 years, thus avoiding a possible complicating factor.

(2) *Outer density* per tree was obtained from rings 23 to 30, averaged for the two radial samples:

$$\textit{Outer density} = \frac{A2 + B2}{2} \quad g\ cm^{-3}$$

Rings 23 to 30 were selected as being the most suitable for comparing sites as the final thinning in most stands rarely took place after 23 years.

(3) *Mean density* per tree = $\dfrac{\textit{Inner density + outer density}}{2}$ g cm^{-3}

(4) *Density gradient* per tree = $\dfrac{\textit{Outer density - Inner density}}{\textit{Inner density}}$ X 100 %

Regression analysis

After determination of plot means, each of the density parameters was used as a dependent variable in regression analysis, with site, stand, and foliar nutrient parameters as independent variables. The regression methods used were those described in Chapter 2.

5.1.3 RESULTS

5.1.3.1 **Summary statistics**

Summary statistics for density parameters are shown in Table 5.1. It is apparent that the parameters do not show a large between-site variation other than in the case of *density gradient*.

Table 5.1 Summary statistics for wood density parameters (147 sites)

Parameter	Units	Mean	Range	Std.dev	C.V.%
Inner density	g cm^{-3}	0,353	0,322-0,398	0,0155	4,4
Outer density	g cm^{-3}	0,474	0,425-0,531	0,0232	4,9
Mean density	g cm^{-3}	0,414	0,382-0,449	0,0158	3,8
Density gradient	%	34,90	16,29-57,08	7,1026	20,4

5.1.3.2 **Within and between-site variation**

Analyses of variance for the four density parameters are shown in Table 5.2.

Table 5.2 Analysis of variance for (i) *inner density*, (ii) *outer density*, (iii) *mean density* and (iv) *density gradient*

(i) *Inner density*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	146	0,00183918	2,07	0,0001	11,80
Within sites (Error)	973	0,00088810			88,20
					100

(ii) *Outer density*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	146	0,00402844	2,03	0,0001	11,38
Within sites (Error)	966	0,00198461			88,62
					100

(iii) *Mean density*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	146	0,00183532	1,77	0,0001	8,81
Within sites (Error)	949	0,00103547			91,19
					100

(iv) *Density gradient*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	146	372,13852	2,89	0,0001	19,09
Within sites (Error)	949	128,89151			80,91
					100

Between-tree variation for *inner density*, *outer density* and *mean density* amounted to approximately 90%. While this indicates that the potential for genetic improvement of wood density is high, it creates difficulties in the study of site differences. Between tree variation for *density gradient* was slightly less. However, in spite of the relatively small between-site variation, site differences were very highly significant.

Sample size in studies of this nature is clearly of great importance. It is apparent from the literature that sample sizes in site-wood density investigations have ranged from 1 to 50 per site, and that many of those studies employing less than 10 trees failed to reveal site differences (e.g. Burley, 1973; Adlard *et al*, 1979; Harrington and De Bell, 1980). Zobel *et al* (1960) recommended 22 as a minimum. From his study in *P.patula*, Turnbull (1947) concluded that 15 trees would be insufficient to overcome genetic variation and recommended a sample size of 30. In the present study the limits imposed by the small size of 8 trees per site, due to the subsidiary nature of the study, are recognized. However, as site differences are nevertheless very highly significant, further analysis was considered justified.

5.1.3.3 **Correlations**

The largest correlation coefficients between wood density parameters and site and stand parameters are shown in Table 5.3. Although the correlation coefficients were very highly significant, they were generally low. They were highest for *density gradient* and lowest for *mean density*, for which there were none greater than 0,3.

5.1.3.4 **Regression analysis**

With wood parameters as dependent variables, separate regression models were constructed for site parameters, stand parameters, foliar nutrient parameters, and finally site plus stand parameters combined, all as independent variables.

Table. 5.3 Correlation coefficients (r) > 0,3 between wood density parameters and site and stand parameters

Site parameters	*Inner density*	*Outer density*	*Mean density*	*Density gradient*
Rainfall	0,37	-	-	-0,36
Altitude	-	-0,31	-	-0,47
Topographic position	-0,30	-	-	-
ERD	-0,47	-	-	0,46
Hue, B hor.	-	-	-	-0,32
Geology	-	-	-	0,40
Ca, A hor.	-	-	-	-0,32
pH (H_2O), A hor.	-	-	-	0,30
Exch. acidity, A hor.	-	-	-	-0,32
Stand parameters				
Site index	-0,48	-	-	0,55
Form factor	-0,38	-	-	0,55
Stem bumps mean size, (bump trees only)	-0,34	-	-	0,32
Stem bumps mean size, (all trees)	-0,38	-	-	0,37
% trees with bumps	0,39	-		-0,37

(All correlation coefficients significant at the 0,0001 level).

Inner density

The model to predict *inner density* from site variables had an R^2 of 0,3357 and contained the following variables: *Rainfall, altitude, slope position, effective rooting depth, B horizon silt, sand* and *aluminium*, and *A hor. Ca*. The stand parameters model contained only two variables, viz. *site index* and *age*, with R^2 = 0,2679. It was not possible to predict *inner density* from foliar nutrients, as the R^2 was only 0,1091. Regression coefficients for the site plus stand parameters model (Model 5.1) are shown in Table 5.4.

Table 5.4 MODEL 5.1: Regression coefficients to predict *inner wood density*.

X	Regress. coeff.	S.D.	Stdd coeff.	t-value	Probability
Site index	-0,00134	<0,01	-0,37	3,99	0,00011
Silt, B hor.	0,00068	<0,01	0,36	2,80	0,00583
Altitude	-0,00002	<0,01	-0,28	2,58	0,01099
Rainfall	0,00002	<0,01	0,27	2,91	0,00420
Vol. of stones, B. hor.	0,00017	<0,01	0,27	3,26	0,00139
Silt, A hor.	-0,00048	<0,01	-0,25	1,92	0,05761
Sand, A hor.	0,00015	<0,01	0,17	1,62	0,10765
Al, B hor.	-0,00497	<0,01	-0,15	2,11	0,03649
Mid/lower slopes	-0,00362	<0,01	-0,12	1,68	0,09449
Intercept	0,37485	0,02			
R^2 = 0,3786		S.E. = 0,013			

Outer density
Regression coefficients for the best model to predict *outer density* are shown in Table 5.5.

Table 5.5 MODEL 5.2: Regression coefficients to predict *outer wood density*.

X	Regress. coeff.	S.D.	Stdd coeff.	t-value	Probability
Altitude	-0,00003	<0,01	-0,26	2,95	0,00377
Exch. acidity, A hor.	-0,00469	<0,01	-0,21	2,39	0,01803
Slope %	0,00033	<0,01	0,19	2,33	0,02126
Coarse sand B hor. (log)	0,01459	0,01	0,18	2,21	0,02910
Intercept	0,49936	0,01			
R^2 = 0,2234	S.E. = 0,021				

Mean Density
Regression coefficients for the best model to predict *mean density* are shown in Table 5.6.

Table 5.6 MODEL 5.3: Regression coefficients to predict *mean density*.

X	Regress. coeff.	S.D.	Stdd coeff.	t-value	Probability
Altitude	-0,00003	<0,01	-0,39	3,57	0,00049
Rainfall	0,00002	<0,01	0,30	2,88	0,00468
ERD (log)	-0,01120	<0,01	-0,29	3,16	0,00195
pH (H_2O) *A hor.*	0,00979	<0,01	0,22	2,38	0,01847
Foot slope	-0,01044	<0,01	-0,18	2,20	0,02918
K, B hor.	-0,00014	<0,01	-0,17	2,01	0,04692
Intercept	0,40167	0,02			
R^2 = 0,2161		S.E. = 0,014			

Density gradient

The model to predict *density gradient* from site variables alone had an R^2 of 0,3897 and contained similar variables to the preceding models, viz. *altitude, slope %, ERD* (log), *coarse sand B. hor , exchange acidity A hor.* and *sand B horizon*. The stand variables model had an R^2 of 0,3589 and contained the variables *site index, volume* and *age*. Regression coefficients were very unstable. The most important variable by far was *site index*, with a positive coefficient. The foliar nutrients model had a coefficient of determination of 0,2161, higher than for other wood parameters, but still very low. Inclusion of *site index* with the site parameter model resulted in an equation with the variables shown in Table 5.7.

5.1.4 DISCUSSION

The generally low coefficients of determination for the wood density models can be ascribed to the large between-tree variation. There was an inverse relationship between R^2 and the percentage of variation attributable to between-tree differences (Table 5.8). Wilkes (1989) found that wood density of *P.radiata* in South Australia could be predicted from *D.B.H.* and *rainfall*, with R^2 = 0,72. In this case between-tree variation was as low as 20%. It may not therefore be correct to state, for example, that *density gradient* was more closely related to site than were the other parameters. The higher R^2 for *density gradient* may have been due to smaller between-tree variation. Similarly, the greater between-tree variation for the other parameters may

Table 5.7 MODEL 5.4: Regression coefficients to predict *density gradient*.

X	Regress. coeff.	S.D.	Stdd coeff.	t-value	Probability
Site index	0,78862	0,15	0,47	5,40	<0,00001
Coarse sand, B hor. (log)	5,36422	1,92	0,22	2,79	0,00601
Foot slope	-4,78340	1,88	-0,19	2,55	0,01203
Exch acidity, A hor.	-1,24162	0,52	-0,18	2,41	0,01737
Vol. stones, B hor.	-0,04665	0,02	-0,16	2,10	0,03803
Sand, B hor.	-0,06365	0,03	-0,16	1,98	0,04968
Slope %	0,06731	0,04	0,13	1,76	0,08116
Intercept	15,87927	4,30			
R^2 = 0,4292		S.E. = 5,730			

Table 5.8 Relationship between R^2 values and within-site variation.

Model	R^2	% variance, within sites (ex Table 5.2)
5.1 *Inner density*	0,3786	88,20
5.2 *Outer density*	0,2593	88,62
5.3 *Mean density*	0,2161	91,19
5.4 *Density gradient*	0,4292	80,91

well have obscured important relationships with site. The sample size of 8 trees per site was insufficient to overcome this problem. Nevertheless, the number of sites sampled was large enough to indicate some significant relationships.

Site index was an important variable in predicting *inner density*, and in the case of *density gradient* it was by far the most important variable. It did not, however, appear in the *outer density* model. *Outer density* was more affected by *altitude* which was the most important variable. Since *site index* can be determined mostly by soil properties (Models 2.6 to 2.12), it can be inferred that wood formed during the first eight years (Model 5.1) is influenced mostly by soil conditions, whereas wood formed towards maturity (Model 5.2) would appear to be influenced more by climate, in the form of temperature (*altitude*). The findings of Cown (1974) and Harris, *et al* (1978) were similar for *P.radiata*. The results show that poorer sites should therefore produce denser pulpwood (higher *inner density*) as well as a more uniform timber (lower *density gradient*). The role of other important variables in the models, especially of *soil texture*, *soil acidity* and *rainfall* cannot be explained. *Rainfall* was also found to be an important predictor of wood density of *P.radiata* in Australia (Wilkes, 1989).

This is possibly the first time that site-density gradient relationships have been studied on any large scale. The only literature references which could be found were two studies in South Africa, in which Turnbull (1947) noted definite density gradient differences between 5 sites, and Van der Sijde (1976) found differences in clonal material between two sites. As *inner density* was more strongly affected by soil (R^2 = 0,38, Model 5.1) than was outer *density* (R^2 = 0,26, Model 5.2), one would expect *density gradient* in turn to be more dependent on variation in *inner density* than in *outer density*. However, correlation coefficients show that *density gradient* was, in fact, more strongly related to *outer density* (r = 0,72) than to *inner density* (r = 0,43). *Density gradient* cannot, therefore, merely be a compensating factor for variation in *inner density* to ensure stem stability. According to Turnbull (1947), the density gradient "would seem to be a device by means of which a state of equilibrium between crown size and the ratio between vertical and radial increment on the one hand, and external transverse forces on the other, is in successive years maintained with maximum economy of material. Disturbance of this equilibrium would render a stem liable to breakage ...." The results of this study do not entirely support Turnbull's theory, but neither do they offer an explanation of the role of *density gradient*.

Although *site index* and rate of growth are related, this should not be interpreted as indicating that wood density is therefore affected by rate of growth, thus conflicting with the well-known findings of Turnbull and Du Plessis (1946) or Turnbull (1947). Turnbull maintained that density would not be affected by rate of growth *once the effect of site was eliminated*. The question hinges on whether the variable *site index* should be interpreted as an expression of rate of growth, or of site quality. Although this may be mere speculation, there is some evidence in support of the former. The fact that variables which do strongly express rate of growth, viz. *D.B.H.*, *present height* and *stems per hectare*, did not appear in any wood density models, either in addition to *site index* or as alternates, lends some support to Turnbull. Certainly the findings do not contradict those of Turnbull.

Wright *et al* (1987 a, 1987 b) have also produced evidence in the case of *P. caribaea* and *P. oocarpa*, that slow growth is not necessarily accompanied by higher density. In contrast to this study, Wilkes (1989) found wood density of *P. radiata* in Australia to be strongly related to D.B.H.

5.2 SPIRALITY

5.2.1 LITERATURE REVIEW

From the literature it is evident that the relationship between wood spirality and environmental factors has received very little attention. In *P.sylvestris* in Norway, spiral grain was found to be the highest in areas of poor growth (Kaasa, 1976). In *P.radiata* in Australia, irrigation and partial droughting had no effect on spirality (Nicholls and Waring, 1977). Neither were any effects detected in clonal material of *P.radiata* subjected to different controlled conditions of moisture and nutrients in New Zealand (Harris *et al*, 1978).

5.2.2 METHODS

Field survey
Spirality determinations were done on the same samples as those for wood density, the field procedure for which was described in para. 5.1.2.

Laboratory determinations
Samples were prepared and grain angles measured on opposite radii according to the method described by Kromhout (1966). Angles were measured on rings 8, 22 and 30, and means determined for the two radii. Occasional changes in grain direction (left or right) between the two radii within the same ring were ignored in the calculation of mean values (Kromhout and Gerischer, 1964). A total of 6960 samples was measured.

Spirality parameters
The following spirality parameters were derived:

1. *Spirality at 8 years*
2. *Spirality at 22 years*
3. *Spirality at 30 years*
4. *Mean spirality* (mean of 8, 22 and 30 years spirality).

Regression analysis
As for wood density (para. 5.1.2).

5.2.3 RESULTS

5.2.3.1 Summary statistics

Summary statistics are shown in Table 5.9

Table 5.9 Summary statistics for wood spirality parameters (146 sites)

Parameter	Units	Mean	Range	Std.dev	CV%
8-year spirality	degrees	3,83	2,06-6,66	0,819	21,4
22-year spirality	"	3,38	1,44-5,75	0,863	25,6
30-year spirality	"	3,36	1,71-5,81	0,766	22,8
Mean spirality	"	3,52	1,96-5,54	0,714	20,3

It can be seen that there was not a large difference between mean *8-year spirality* and mean *30-year spirality*. Far larger differences were found within individual trees, but as many trees showed a reverse trend (higher outer than inner spirality), the mean difference was not large.

To evaluate the theory proposed by Kromhout and Gerischer (1964), that spirality in *P.patula* is mainly to the left at an early age but with a tendency towards increasing right-hand spirality at older ages, the percentage of individual trees with right-hand spirality was determined for each of the three ages. The results are shown in Table 5.10, confirming the trend towards an increasing percentage of right-handed spirality.

Table 5.10 Percentage of trees with right-hand spirality at different ages (n = 1040)

Age	Trees with right-hand spirality
8	18,50%
22	31,41%
30	37,64%

5.2.3.2 Within and between-site variation

Analysis of variance for the four spirality parameters are shown in Table 5.11.

Between-tree variation for wood *spirality* of *P.patula* was even greater than in the case of wood *density*, reaching 99,9% for *30 year spirality*. As a result, although there were significant differences between sites, significance levels were much lower than in case of density parameters, and *30 year spirality* was in fact not significant. For the proper study of site effects, very large sample sizes would therefore be required.

5.2.3.3 Correlations

Correlation coefficients between wood spirality parameters and site and stand parameters were low. In only two cases were correlation coefficients higher than 0,3 (Table 5.12).

5.2.3.4 Regression analysis

With wood spirality parameters as dependent variables, separate regression models were constructed for site parameters, stand parameters, foliar nutrient parameters, and finally site plus stand parameters combined, as independent variables.

8-year spirality
Coefficients of determination for prediction models were:

R^2 = 0,2910 for site parameters
R^2 = 0,1048 for stand parameters
R^2 = 0,0734 for foliar parameters
R^2 = 0,3558 for site plus stand parameters

The site plus stand parameters model had the highest R^2, but the only stand parameter in this model was *total basal area*. As its role is not clear and as it contributed little to the efficiency of the model, the model with site parameters only is more easily understood. Coefficients are shown in Table 5.13.

Table 5.11 Analysis of variance for (i) *8 year spirality* (ii) *22-year spirality* (iii) *30 year spirality* and (iv) *mean spirality*.

(i) *8 year spirality*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	145	5,22629812	1,31	0,0112	3,79
Within sites (error)	996	3,97465490			96,21
					100

(ii) *22-year spirality*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	145	5,88533942	1,35	0,0056	4,43
Within sites (error)	994	4,34511395			95,57
					100

(iii) *30-year spirality*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	145	4,55345143	1,00	0,4735	0,06
Within sites (error)	992	4,53331201			99,94
					100

(iv) *Mean spirality*

Source	d.f.	Mean Square	F	Pr > F	% Variance (random model)
Between sites	145	4,00978278	1,28	0,0210	3,35
Within sites (error)	992	3,14021989			96,65
					100

Table 5.12 Correlation coefficients (r) > 0,3 between wood spirality parameters and site and stand parameters

Site parameters	*8-year spirality*	*22-year spirality*	*30-year spirality*	*Mean spirality*
Altitude	0,33	0,34	-	0,33
ERD	-	-0,34	-	-0,35

(Significant at 0,0001 level)

Table 5.13 MODEL 5.5: Regression coefficients to predict *8-year spirality* from site parameters

X	Regress. coeff.	S.D.	Stdd coeff.	t-value	Probability
pH (H_2O), B hor.	-1,00978	0,28	-0,36	3,61	0,00043
Total sand, B hor.	0,01681	<0,01	0,35	4,13	0,00006
P, A hor.	-0,05730	0,02	-0,26	3,40	0,00088
Slope %	0,01663	0,01	0,26	3,29	0,00129
Ca, A hor. (log)	0,41664	0,15	0,26	2,86	0,00495
Coarse sand, A hor.	-0,02239	0,01	-0,23	2,84	0,00520
ERD (log)	-0,31828	0,18	-0,16	1,75	0,08262
Al, B hor.	-0,25708	0,15	-0,14	1,68	0,09566
Intercept	8,79895	1,32			
R^2 = 0,2910		S.E. = 0,710			

Other spirality parameters

Coefficients of determination for all other spirality parameters were low:

R^2 = 0,1737 for *22-year spirality*

R^2 = 0,1488 for *30-year spirality*

R^2 = 0,2707 for *Mean spirality*

As such a small proportion of the total variation was explained by site differences, no further details are given.

5.2.4 DISCUSSION

The low predictive ability of the models can be ascribed to an inadequate sample size to compensate for between-tree variation. The large sample size necessary for a site study such as this would require large resources. On the other hand, the potential for genetic improvement with regard to this defect, is high as a result. The model to predict *8-year spirality* had a higher coefficient of determination than that for *22-year* or *30-year spirality*, probably due to the decrease in spirality with increasing age (Table 5.9). Most of the variables in Model 5.5 indicate that spirality decreases with an improvement in general site conditions. This was confirmed by several other possible models, all of which contained similar variables to Model 5.5, but with the variables in different orders of importance. For example, the sign of the coefficient for *total sand* in Model 5.5 was positive, whereas in other models *total sand* was replaced by *silt* content with a negative coefficient. This implies that spirality was higher on coarse-textured soils and lower on silty soils.

5.3 STEM BUMPS

5.3.1 LITERATURE REVIEW

Surface irregularities other than cankers on the stems of forest trees have variously been termed bumps, swellings, ridges, bulges, knobs, and protuberances (Banks, 1956; De Villiers, 1974; Mergen and Winter, 1952; Phillips and Patterson, 1965; Tressel, 1970). Locally they have also been described as nodal swellings, lumps, corrugations or mae wests. For the purposes of this study the term "bumps" will be used.

Reports on bumps resulting from compression failure after severe wind storms have been reviewed by Mergen and Winter (1952). They found that bumps developed as reaction to compression failure on the leeward side of the stem, were usually diagonal across the stem, were common in young trees with low taper, were gradually obscured within ten years, and occurred in several conifer species in Europe and the USA. Sitka spruce suffered this type or damage after a gale in the U.K. (Phillips and Patterson, 1965).

Extensive damage to *P. patula* stands at Weza State Forest resulted from gale-force winds in June, 1967. A subsequent study by Tressel (1970) revealed that bumps had developed on the leeward side of the stems, indicating severe compression breaks in most cases. These bumps were more numerous than the more typical nodal bumps, occurred on the internodes and extended on average for one eighth of the circumference of the stem. They were associated with heavier timber and a steeper density gradient than undamaged timber. No compression breaks or leeward bumps occurred in adjoining stands of *P. elliottii* and *P. taeda*, and Tressel ascribed the damage in *P. patula* to its denser crown offering more wind resistance than in the case of the former two species. Similar problems occurred again at Weza after a storm in 1970 (Gerischer, *et al*, 1976). *P. patula* stands are most susceptible to wind damage and compression bumps from 18 years onwards (Gerischer *et al*, 1976; Le Roux, 1955).

Judging by the lack of reference overseas, the type of bump which is mostly nodal and *not* associated with compression failure appears to be a problem confined to *P.patula* in southern Africa. According to Banks (1956), these bumps are found at the nodes, are more pronounced on pruned than on unpruned stems, are greater on one side of the stem than on the opposite face, and are larger near the butt than higher up the stem. Banks found that the outer wood density of bumpy logs was higher than that of material free of bumps. He could offer no explanation as to the cause of these bumps. However, De Villiers (1974) noted that bumps were more common in warmer zones and in older trees. It has been observed that nodal bumps start to develop from about the 16th year onwards, but that there is a large between-tree and between-site variation.

From the literature it is apparent that there exists a reasonable explanation for the formation of bumps in wind-damaged trees, but that no reason can be found for the development of nodal bumps or their relationship with environmental factors.

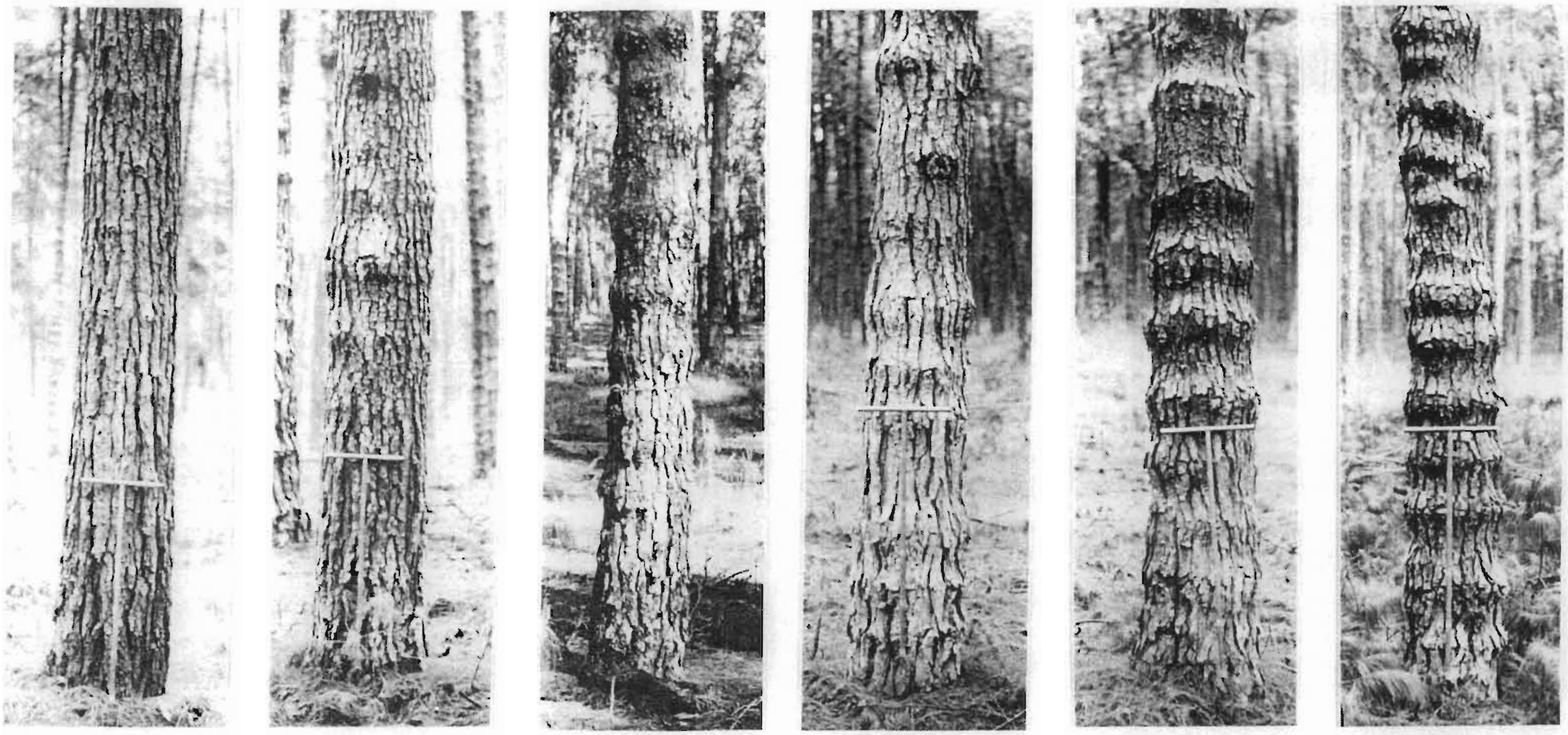
5.3.2 METHODS

Pilot study

To obtain more information on the relationship between bumps and internal wood properties such as nodal position, occlusion of branch stubs since pruning, knot size, compression breaks and other defects, two mature stands of *P. patula* with severe bump development were selected on Mac Mac State Forest for sampling and dissection of logs. At each site 20 trees representing different types and degrees of severity of bumps were felled. A 3 m butt log from each tree was sawn into boards which were kiln-seasoned and planed, taking care not to damage the bumps unduly. Boards sawn through the pith were assessed for the above parameters.

Field survey

Bumps were assessed on the basal 3 m of each tree on each of 149 0,1 ha plots used in the site index study (Ch. 2, para. 2.4), as follows: (1) Size index: Visual assessment on a scale 0 to 5 - the zero index indicating a "clean" stem, the 5 index a stem with the largest size of bumps (Fig. 5.1) (2) Extent in horizontal plane, i.e. whether all round the stem or more strongly developed on one side only. (3) Orientation (if on one side of the stem only).



0 1 2 3 4 5

Figure 5.1 Bump size index of P. patula (visual assessment).

The mean number of trees per plot thus assessed was 34, the total over all plots 5311. From these assessments the following parameters were derived:

		CODE
Mean size index of oriented bumps, trees with bumps only	:	*SIZORIENT*
" " " " all-round bumps, " " " "	:	*SIZROUND*
" " " " all bumps, " " " "	:	*SIZBOTH*
" " " " all bumps, all trees	:	*SIZALL*
Cumulative %, all trees with ≤ index 5 bumps	:	*SIZ 5%*
" " " " " " " 4 "	:	*SIZ 4%*
" " " " " " " 3 "	:	*SIZ 3%*
" " " " " " " 2 "	:	*SIZ 2%*
" " " " " " " 1 "	:	*SIZ 1%*
% of trees with bumps which have oriented bumps	:	*ORIENT %*
" " all trees with oriented bumps	:	*ORIENT % ALL*
" " " " " all-round "	:	*ROUND % ALL*

Regression analysis procedures to determine the relationship between bumps parameters and environmental parameters were the same as those used in the case of wood density (par 5.1.2).

5.3.3 RESULTS

5.3.3.1 **Pilot study**

The study of boards sawn from trees with different types and degrees of severity of bumps revealed the following:

(1) Compression breaks in the timber were rare, confirming what has already been found in the Eastern Transvaal generally (Tweefontein Timber Co., pers. comm.). In a similar study of logs from *P. patula* trees with severe bumps from four stands at Entabeni State Forest, Banks (1956) made no reference to compression breaks and could presumably not find any.

(2) Bumps were mostly nodal. (Fig. 5.2).

(3) Those that were not nodal appeared to have been caused mostly by hail damage. (Fig. 5.3).

(4) Bumps caused severe grain deflection depending on their size. Grain

separation may even occur within severe bumps (Fig. 5.4). This confirms the findings of Banks (1956).

(5) With few exceptions bumps started developing immediately after pruning. However, not all pruned stems developed bumps, confirming Banks' findings.

(6) There was no correlation between knot size and bump size.

(7) The age at which bumps started developing depended on the date of pruning and ranged from 2 to 8 years.

(8) Bumps usually increased in size with age, but sometimes decreased, or decreased then increased, or disappeared and reformed later.

(9) Bumps more strongly developed on one side of the stem were found exclusively in trees with eccentric growth, and always on the side closest to the pith. (Fig. 5.5).

5.3.3.2 Field survey summary statistics

Summary statistics of the parameters recorded are shown in Table 5.14.

Table 5.14 Summary statistics for stem bumps parameters

Parameter	n	Mean	Range	Std.dev	C.V.%
SIZORIENT	101	4,121	3,00-5,00	0,477	10,9
SIZROUND	149	4,539	2,50-5,00	0,409	9,0
SIZBOTH	149	4,482	3,04-5,00	0,390	8,7
SIZALL	149	4,580	3,14-5,29	0,401	8,8
SIZ 5%	149	0,06	0 - 4	0,438	725,9
SIZ 4%	145	1,5	0 - 28	4,232	275,4
SIZ 3%	149	10,66	0 - 72	13,046	122,3
SIZ 2%	149	36,62	0 - 90	23,182	63,3
SIZ 1%	149	93,15	68 - 100	7,811	8,4
ORIENT %	149	22,63	0 - 97	29,298	129,5
ORIENT % ALL	149	21,25	0 - 91	27,567	129,7
ROUND % ALL	149	71,89	3 - 100	27,656	38,5

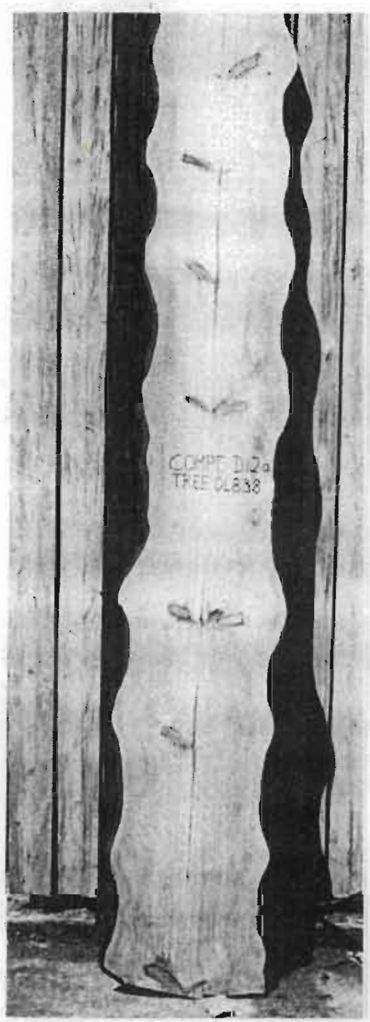


Figure 5.2 Bumps are mostly nodal.

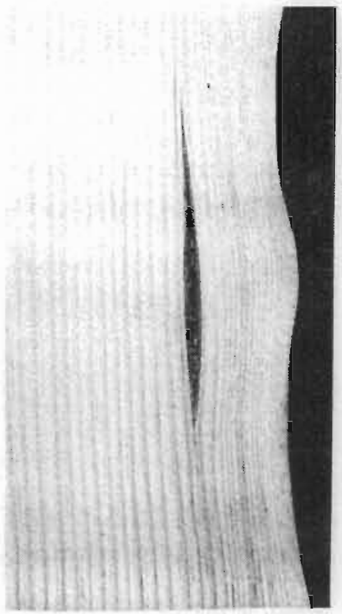


Figure 5.3 Bump caused by hail damage.

Figure 5.4 Grain deflection and separation.

Figure 5.5 Bumps only on one side, closest to eccentric pith.

From Table 5.14 the following deductions can be made:

(1) All-round bumps tended to be slightly smaller than oriented bumps (mean index 1,461 vs 1,879).

(2) Only 7% of the 5311 trees assessed had completely smooth stems, and on some sites none were found. This is shown more clearly in Fig. 5.6.

(3) Assuming that a bump index of 3 and over would be likely to cause serious defects in the timber, approximately 10% of all trees in mature stands had serious bumps. (Fig. 5.6).

(4) The majority of trees had bumps around the circumference of the stem. In contrast, trees from Entabeni State Forest studied by Banks (1956) had no all-round bumps. In this study 23% of trees with bumps had bumps more strongly developed on one side. Some trees carried both types of bump. Some sites carried trees with all-round bumps as well as trees with oriented bumps. Usually if orientation occurred, most trees in the stand were oriented, and mostly in the same direction.

The orientation of bumps is not shown in Table 5.14. Instead the percentages of trees with bumps of different orientations are shown diagramatically in Fig 5.7, from which it can be concluded that the orientation of bumps was strong northerly, north-westerly and to a lesser extent southerly. Few bumps faced north-east, south-west or south-east.

5.3.3.3 Correlations

In view of the large numbers of bumps parameters and generally low correlations with site and stand parameters, correlation coefficients are not shown. Coefficients for stand parameters were higher than for site parameters, but all below $r = 0,5$.

5.3.3.4 Regression analysis

The bumps parameters listed in Table 5.14 all had potential for use as dependent variables in regression analysis. As it would have been a heavy task to have attempted to construct models for each of them, it was decided

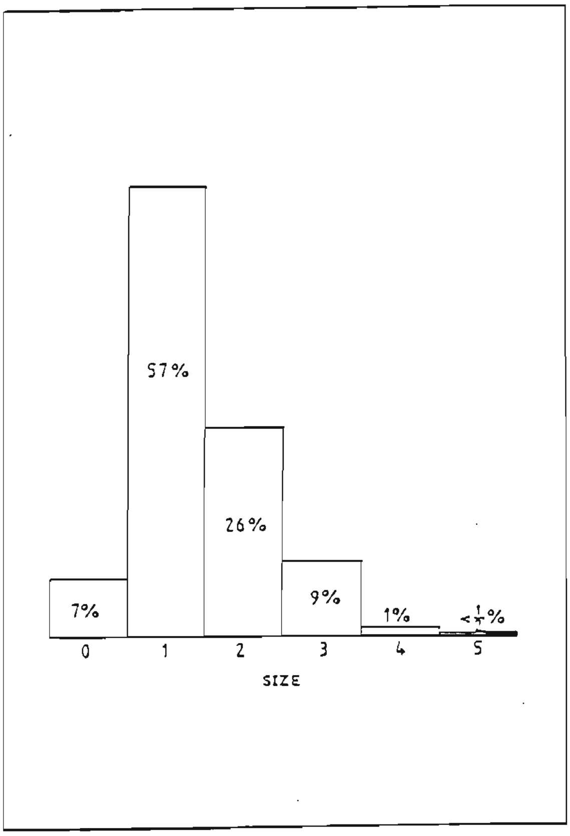


Figure 5.6 Histogram of percentages of 5311 *P.patula* trees by bump size index.

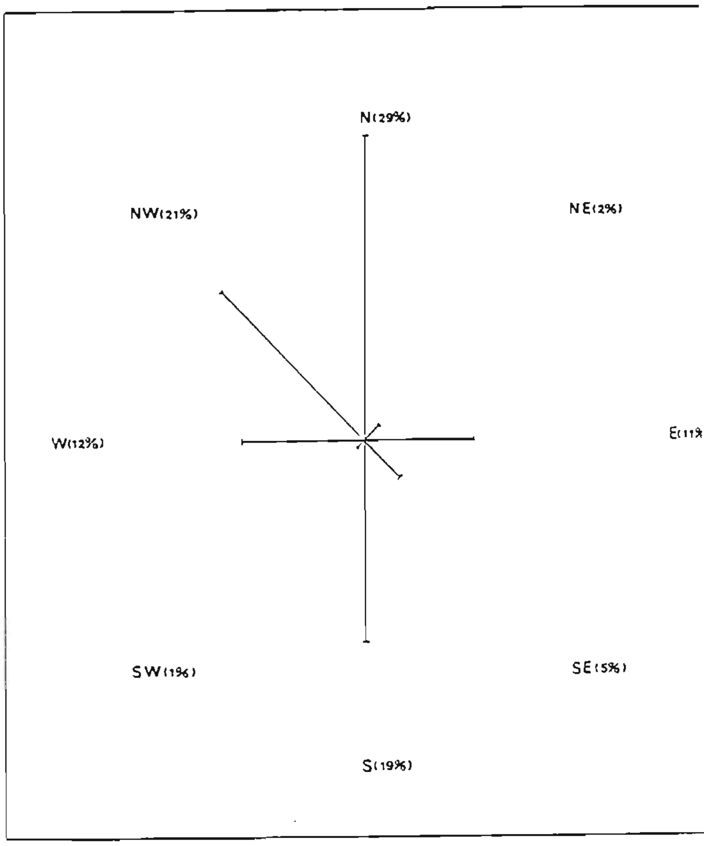


Figure 5.7 Orientation of stem bumps on 1222 *P.patula* trees.

instead to select only those with the highest potential. Variables *SIZORIENT*, *SIZROUND*, *SIZ 5%*, *SIZ 4%*, and *SIZ 3%* were discarded as either too few plots were available, or plot means were based on too few trees (sometimes only one). From the remaining variables it was decided to select the best one expressing bump size and the best expressing bumps percent. This was done by running preliminary regression analyses with site parameters as independent variables and selecting the dependent variables which gave the highest coefficients of determination. Variables *SIZALL* (mean size index of all bumps, all trees) (R^2 = 0,45), and *SIZ 2%* (cumulative percent of trees with bump index equal to or larger than index 2 (R^2 = 0,50), were selected. For convenience *SIZALL* will be referred to as *mean bump size index* and *SIZ 2%* as *percentage of trees with bumps*.

Using the independent variables described earlier (para. 5.1.2), with wood parameters in addition, regression models were constructed for site parameters, stand parameters, site plus stand parameters and foliar nutrient parameters. Models to predict *bumps size index* were found to differ only slightly from models to predict *percentage of trees with bumps*. As there was also a high correlation between these two dependent variables (r = 0,96), it was not considered necessary to distinguish between the two, and a choice was made on the basis of coefficients of determination. *Percentage of trees with bumps* had the higher R^2 (0,6144 vs 0,5690 for the full models), and *bumps size index* was therefore not considered further. All models predicting *percentage of trees with bumps* required a square root transformation of this variable.

The site parameters model contained the following variables in approximate order of importance: *Altitude, rainfall, B horizon Mg*, four categories of *B horizon hue, A horizon Ca*, (log), Selati substrate, *B horizon thickness, A horizon coarse sand* and *B horizon P*, with R^2 = 0,5466. The model with stand parameters contained the variables *age, mean DBH, bark thickness* and *outer wood density*, but as the R^2 was low (0,3127) they did not appear to have a key role. The most important variable by far was *age* of stand. Foliar nutrients explained only 19% of the severity of bumps. When site and stand parameters were combined, a useful model was obtained for the prediction of the severity of bumps (Model 5.6, Table 5.15)

5.3.4 DISCUSSION

5.3.4.1 Oriented bumps

The fact that bumps were so closely aligned with specific compass bearings (Fig. 5.7) indicates that wind probably plays an important role in the formation of stem bumps in *P. patula*. Oriented bumps were mostly in a northerly and north-westerly direction, and to a lesser extent southerly. It has already been shown that oriented bumps occurred exclusively in trees with eccentric pith (para 5.3.3.1), and always on the side closest to the pith. As eccentricity of the pith in conifer stems is in the direction of the prevailing wind (Busgen *et al*, 1929), it can be deduced that oriented bumps must therefore develop on the windward side, i.e. during spring when prevailing winds are northerly. The problem with this hypothesis is that wood is stronger in tension than in compression (Mergen and Winter, 1952), and that the reported cases of storm damage have all clearly shown that bumps resulting from compression failure have always been on the *leeward* side of the stems. There is, however, a plausible explanation in the case of the Eastern Transvaal. Since the wider annual rings on the leeward side of the eccentric pith is a strengthening of the stem in reaction to stress from the opposite side, it follows that wood on the shorter axis should be weaker when that stress is not present. The resistance of this weaker wood to severe storm winds from the opposite direction in summer would be greatly reduced, the

Table 5.15 MODEL 5.6: Regression coefficients to predict *percentage of trees with bumps* (square root)

X	Regres. coeff.	S.D.	Stdd. coeff.	t-value	Probability
Altitude/100, cent.	-0,48016	0,07	-0,51	6,99	<0,00001
(*Alt*/100,cent)^2 cent.	-0,05648	0,02	-0,19	3,27	0,00136
Age	0,15337	0,03	0,36	5,55	<0,00001
Rainfall	0,00280	<0,01	0,34	4,00	0,00011
Mg, B hor.	-0,04449	0,01	-0,30	4,05	0,00009
Hue, B hor:					
2, 5 YR	1,13144	0,38	0,26	2,95	0,00374
3,75 YR	1,68018	0,70	0,15	2,40	0,01770
5, 0 YR	0,90148	0,42	0,19	2,15	0,03368
7, 5 YR	1,41751	0,49	0,22	2,87	0,00480
10 YR	0,00000	(ref. cat.)			
Ca, A hor. (log)	0,90012	0,33	0,21	2,72	0,00733
B hor. thickness	0,00952	<0,01	0,18	2,80	0,00588
Crest & upper slopes	0,00000	(ref. cat)			
Mid & lower slopes	-0,45896	0,28	-0,11	1,79	0,07648
Foot slope	-1,16622	0,56	-0,15	2,09	0,03826
Selati	0,97601	0,49	0,12	1,98	0,04976
Intercept	-6,50024	1,33			
R^2 = 0,6144		S.E. = 1,428			

compression forces thus causing the formation of bumps.

The fact that bumps are more frequent in the lower part of the stem is further evidence in support of the role of wind. The lower part of the stem has less "give" and so a crumpling effect is produced on the leeward side (a more apt term for bumps would therefore be "crumples"). Since the nodes (whether pruned or not) are zones of weakness, particularly because of the whorled branching habit of *P.patula*, this is where most of the bumps develop, to compensate for cumulative compression stresses over many years. This process would be more gradual than in the case of the rapid development of bumps in response to violent storm winds as recorded at Weza State Forest, but the cause could be essentially the same.

This explanation could be valid for oriented bumps, but 77% of the trees assessed had bumps all around the circumference of the stem. Although it is difficult to prove, it is likely that allround bumps are in fact leeward bumps caused by the cumulative effect of winds from different directions (turbulence), as determined by local topography and exposure. The fact that most stands seldom comprise trees with both oriented and allround bumps, i.e. stands have either the one or the other type of bumps, also lends support to this hypothesis.

5.3.4.2 Quantitative site and stand factors (Model 5.6)

The proportion of the total variation in the percentage of trees with bumps explained by quantifiable parameters was 61,44%. It is reasonable to assume that the wind effects described above would account for a fair proportion of the balance of variation, were it possible to quantify these effects and include them in the model. Such a model would then probably account for the major proportion of the total variation in the severity of bumps.

Altitude was the most important variable in Model 5.6. The percentage of trees with severe bumps was found to be highest at low altitude, decreasing sharply between 1200 and 1800 m to a very low percentage at the highest altitude (Fig. 5.8). The relationship was best expressed by a quadratic function once a square root transformation had been applied to the dependent variable. It is known that trees are shorter at high altitude (Fig 2.9) and thus have a higher taper (Loveday, pers. comm.). This would result in stronger stems less susceptible to wind stresses and thus bump development. Although a relationship between bumps severity and *form factor* could not be confirmed due to the confounding effect of variation in stocking densities, this is nevertheless a possible explanation.

Age was the next variable in importance and was the only stand parameter to appear in the model, confirming the findings of the pilot study (para. 5.3.3.1) that most bumps increase in size with age. This could be related to stem stability. *P. patula* is known for its habit of developing wide, rounded crowns

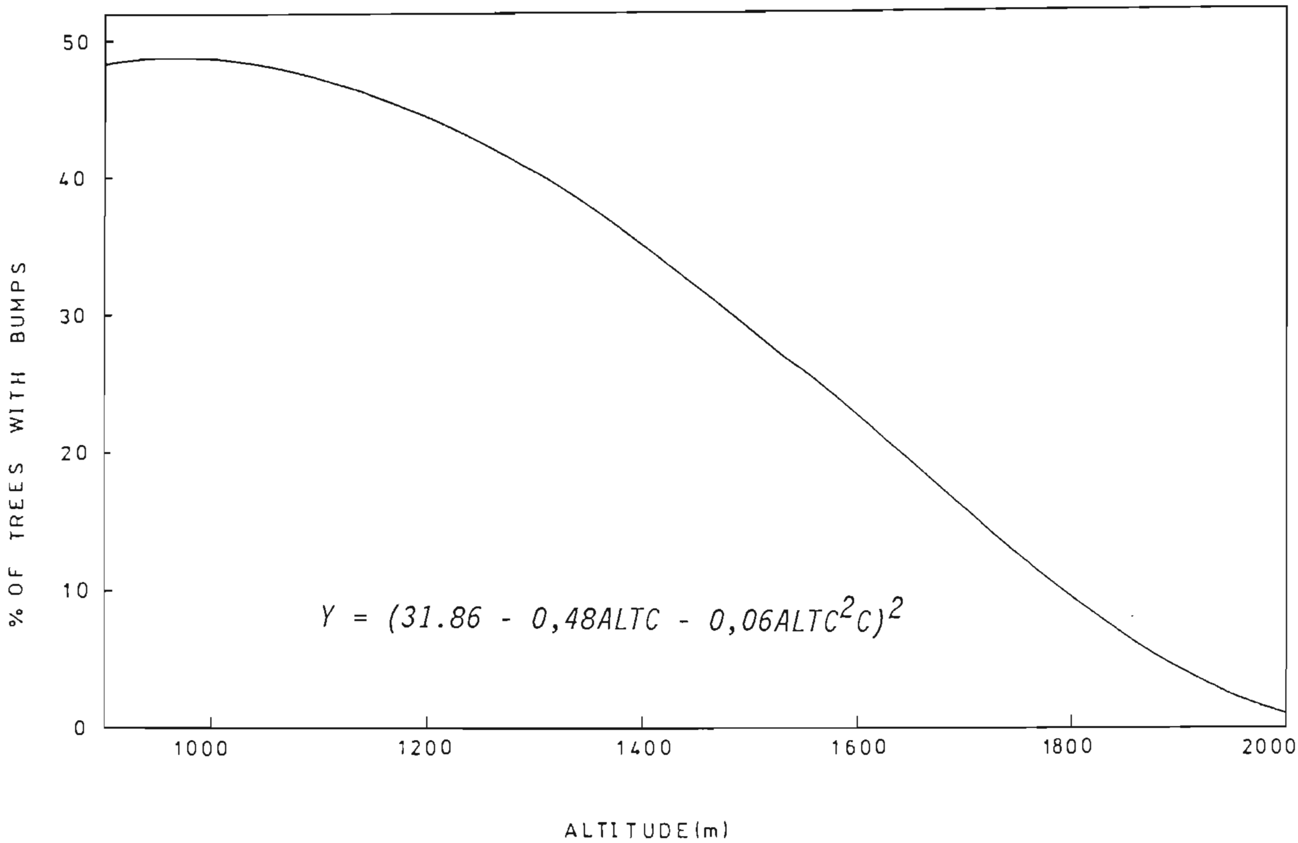


Figure 5.8 Relationship between *percentage of trees with bumps* and *altitude*, with all other variables in regression held at mean values.

as a result of the gradual loss of apical dominance with increasing age, in contrast with other pine species. This concentration of heavy branches near the top of the tree would cause stem instability, particularly under windy conditions. An indication of this is the high incidence of bad stem form in many older stands.

Rainfall was also an important variable. Bumps increased in severity with increasing rainfall.

Magnesium of the B horizon was next in importance. The inverse relationship implies that bumps were less severe on soils well-supplied with Mg.

Hue of the B horizon was represented by four categories towards the yellow end of the spectrum, their presence indicating an increase in the severity of bumps with increasing yellowness (i.e. wetness) of the subsoil. A possible explanation is that tree roots restricted by wet soil conditions would tend to reduce stem stability and thus produce bumps as a reaction. Further support for this hypthesis is lent by the fact that high *rainfall*, which increases soil wetness, had a similar effect (see above).

Calcium of the A horizon and *thickness* of the B horizon were both positively related to the percentage of trees with bumps, but with no apparent explanation.

The percentage of bumps was greatest on *crest/upper slope* positions, less on *mid/lower slopes* and least on *foot slopes*. This would once again tend to indicate a wind effect, bumps being more frequent on exposed ridges and progressively decreasing downslope to the shelter of the valleys.

The *Selati* substrate was the only geological category to appear in the model. The most severe bumps were found on this substrate. This, too, could be a wind effect, as the Selati Formation generally occurs closest to the exposed edge of the Escarpment.

The stand parameters model also identified *D.B.H*, *bark thickness* and *outer wood density* as playing small roles. The role of *D.B.H* is not understood. *Bark thickness* was thinner in trees with larger bumps. This is more likely to have been an effect than a cause, however, as the loose bark flakes characteristic of mature *P.patula* trees in the area would be more easily dislodged and shed from irregular stem surfaces. Larger bumps were also found in trees with a high *outer wood density*, confirming the findings of Banks (1956) and Tressel (1970). High outer wood density is probably another reaction to a weakening of the stem at the branch whorls, caused by wind.

A strong relationship between stem bumps and *stems per hectare* would have been expected, as stems would be more unstable in stands of high density than of low density. *Stems per hectare*, however, did not appear in any of the models in spite of the wide range in stocking (210 - 540 N ha^{-1}). A possible explanation is that although widely spaced trees would have greater stem stability (higher taper), this effect could be neutralized by the heavier branching of the crowns, rendering these stems as unstable as those with smaller crowns and lower taper in stands of higher density.

5.3.4.3 Other observations

It is possible that higher coefficients of determination might have been obtained had a less subjective method of assessing bump size been used. For example, bumps of the same size would appear to be larger on trees of smaller D.B.H than on trees of large D.B.H. This could also explain why models to predict *percentage of trees with bumps*, which is a less subjective parameter than *bump size index*, had higher R^2 values than in the case of the latter.

There was a wide variation in the number of trees with bumps within sites, indicating probable genetic differences. From observations in pruned and unpruned stands (e.g. C.C.T. experiments), pruning does not affect the severity of bumps.

5.4 CONCLUSIONS

5.4.1 DENSITY

1. Between-tree variation to a large extent overshadowed between-site variation, indicating good potential for genetic improvement. Site differences were nevertheless very highly significant. A sample size of between 20 and 30 trees per plot is recommended in future studies. Use of clonal material would greatly simplify this type of research.

2. *Density gradient* was more closely related to site than was any other parameter. This may have been due to smaller between-tree variation than in the case of the other density parameters. In regression models, site factors explained 43% of the total variation in *density gradient*, 38% in *inner density* and 22% in both *outer density* and *mean density*. Coefficients of determination would probably have been higher with a larger sample size.

3. One of the most important variables in the model to predict *inner density* was *site index*, an expression mainly of soil properties. With increasing *site index*, *inner density* decreased. The most important variable in the model to predict *outer density*, on the other hand, was *altitude*, an index of temperature. With increasing altitude, *outer density* decreased. Wood formed during the first eight years would thus appear to be influenced mostly by soil conditions, whereas wood formed later in the rotation is influenced more by climate (temperature).

4. Of all wood density parameters *density gradient* was the most strongly related to site. The most important variable in the model was *site index*. *Density gradient* was more dependent on variation in *outer density* than in *inner density*, but its function remains uncertain.

5. The fact that *site index* was an important predictor of *inner density* does not necessarily conflict with the findings of Turnbull (1947) that density is not affected by growth rate, for a specific site.

6. Stand parameters did not appear to play an important role in determining wood density.

5.4.2 SPIRALITY

1. Between-tree variation, and even within-tree variation, overshadowed between-site variation to an even greater extent than in the case of density, and made conclusions regarding site relationships difficult. Again, the potential for genetic improvement would appear to be good.

2. In regression models site factors explained 29% of the total variation in *8-year* spirality, 17% in *22-year* spirality, 15% in *30-year* spirality, and 27% in *mean spirality*.

3. Spirality decreased with an improvement in general site properties.

4. Spirality generally decreased from 8 years to 30 years.

5. The number of trees with right-hand spirality increased from 19% at 8 years through 31% at 22 years to 38% at 30 years.

5.4.3 STEM BUMPS

1. Compression breaks in timber from trees with bumps were rare, but severe grain deflection and even grain separation usually occurred.

2. Most bumps were nodal, or caused by hail damage.

3. With few exceptions bumps started developing after pruning, but not all pruned trees developed bumps. There was no correlation between knot size and bump size. Bumps usually increased in size with age, but caused grain deflection from an early age.

4. Only 7% of the 5311 trees assessed had completely smooth stems. 10% of all trees in mature stands had severe bumps.

5. 23% of trees with bumps had bumps more strongly developed on one side, mostly on the north to north-west side but to a lesser extent on the south side. These bumps were found exclusively in trees with eccentric growth and always on the side closest to the pith.

6. There are grounds for believing that wind may be the major cause of stem bumps:

(i) Bumps which were more strongly developed on one side of the stem were not randomly oriented but faced in specific compass directions.

(ii) Bumps were least severe at high altitude. As trees at high altitude are shorter and have a higher taper, stems should be stronger than at lower altitude.

(iii) Bumps were more severe under high rainfall and wet soil conditions. As root development is adversely affected by wet soil, stem stability could be reduced.

(iv) Bumps were more severe on ridge tops than on mid and lower slopes, and least severe on foot slopes. In this case *slope position* is probably an expression of exposure.

(v) Bumps were more severe on *Selati* substrate, the only category of geology to appear in models. As the Selati Formation is located along the exposed edge of the Escarpment, this could also indicate a wind effect.

(vi) Bumps increased in size with *age*. The tendency of *P. patula* to develop wide, heavy crowns with increasing age results in a decrease in stem stability.

If these factors can be accepted as being related to susceptibility to wind stresses, then it is likely that bumps are a response to these stresses at the zones of greatest weakness on the bole, viz. at the nodes, and in the lower part of the bole, where these stresses are likely to be strongest.

7. The prediction model which contained the variables described under para. 6 (ii) - (vi) above as well as other predictors with less clear roles, accounted for 61,44% of the total variation in the percentage of trees with bumps.

8. The higher outer wood density found in trees with severe bumps is probably another type of reaction to wind stresses.

9 The wide range in the percentage of trees with bumps within sites could indicate possible genetic differences.

10. Silviculture appears to have little influence.

5.4.4 GENERAL

1. Wood properties were poorly predicted by foliar nutrient concentrations.

2. The higher R^2 values for models predicting the severity of bumps than for models predicting density and spirality can be attributed to the larger sample size per site of the former. (n = 34 for bumps, 8 for density and spirality).

5.4.5 FURTHER RESEARCH

1. Between-tree variation is a difficult problem in attempting to determine relationships between site and wood properties. Research should be directed towards the use of clonal material as the only means of obtaining adequate information.

2. Between-tree variation offers good opportunities for tree improvement, but unless the effects of site are taken into consideration, results could be uncertain. For example, genetic improvement for stem bumps can only be achieved through progeny testing on susceptible sites. The model can be used to identify such sites.

3. Experimental verification of the causes of stem bumps presents feasibility problems. However, a study of the relationship between stem bumps and form factor (in C.C.T. experiments) might help to confirm the role of wind as the most likely cause.

CHAPTER 6

SUMMARY

The study area comprises some 170 000 ha of timber plantations along the Eastern Transvaal Drakensberg Escarpment north of Nelspruit, between 24°31 and 25°22′ south latitude, and 30°25′ and 31°02′ east longitude. Within the region afforestation was undertaken with little knowledge of site conditions or site requirements of the species. Today environmental conditions and their relationships with important tree parameters remain poorly understood. The decreasing availability of land for afforestation in southern Africa and the consequent need to increase productivity per unit area makes a knowledge of these relationships an urgent necessity. The purpose of this study was therefore to examine site-tree relationships within the region defined above and the implications of such relationships. *Pinus patula* Schiede & Deppe in Schlecht. & Cham. was selected for the study as it is the most widely planted species, not only within the study area, but in the whole of southern Africa.

6.1 REGRESSION MODELS

Regression techniques were used to identify and model site-tree relationships. An essential prerequisite was an intensive study of the climate, geology, geomorphology, topography and soils of the area.

At each of 159 sites, selected in mature *P.patula* stands so as to cover the widest variation in site and tree parameters, 100 site factors were assessed as independent variables. Tree growth parameters, as well as litter and wood properties, were recorded as dependent variables at each site and foliar nutrient concentrations analysed in addition. Best-subsets and multiple regression, with ridge regression where necessary, were used to construct models relating the dependent and independent variables.

Site index

In a comparison of nine possible dependent variables, *site index*, defined as top height at 20 years based on the mean of 10 of the 30% largest D.B.H. trees, was the expression of tree growth most accurately predicted from site variables. On the basis of R^2 and validation on 20 new plots established for the purpose, a model using field-measurable site factors only was selected from among several candidates for *site index* prediction (Model 2.12).

The *site index* of the validation plots was predicted with an absolute mean deviation of 0,36 m from the measured *site index* by this model, which makes it satisfactory for both research and management purposes. *Geology, effective rooting depth, volume of stones in the B horizon, altitude* and *slope position* were the site factors included in the model.

Foliar nutrient concentrations

Nearly 60% of the total variation in *site index* was accounted for by a model (Model 3.1) containing the foliar nutrient variables log *Ca*, log *Mg*, *K*, *B* and *Al*. Nutrient ratios were less effective in predicting *site index*. However, the DRIS system showed greater potential for the diagnosis of the nutritional status of trees. Provisional DRIS norms for *P. patula* were computed, based on winter sampling. There was a close relationship between foliar and soil nutrients for the six major geological substrates.

Litter properties

Undecomposed litter was thicker than 15 cm on nearly 25% of the 159 sites sampled. Some of the environmental factors associated with variation in *litter thickness* were identified by regression models which accounted for up to 71% of the variation. The predictors in these models gave an indication of the reasons for excessive litter accumulation. Important variables were *site index, altitude* and a combination of factors related to *soil wetness*. These factors are considered to act indirectly by promoting or retarding the activity of decomposition micro-organisms. Model 4.4 is recommended for prediction purposes. There was some uncertainty whether the high acidity of the topsoil and of the litter which were associated with slow decomposition, was a cause or an effect. There was some evidence in support of the latter. The mass of nutrients in litter of average thickness exceeds that of the underlying topsoil, particularly in the case of P, Ca and probably N. Differences widen as litter thickness increases. However, due to the presence of tree roots in the litter, the extent to which nutrients are immobilized is uncertain.

Wood properties

Extracted wood density was determined on the felled trees from most of the 159 plots. Prediction models for *inner density, outer density* and *density gradient* revealed that variation in the density of wood formed during the early years is associated mostly with soil conditions, whereas that of wood formed in late rotation is associated more with climate. *Density gradient* was most strongly related to site. R^2 values were low due to between-tree variation.

Spirality measurements on the same samples showed decreasing spirality towards the outside of the stem. Prediction models indicated a decrease in spirality with improvement in general site conditions. Excessive between-tree variation to a large extent overshadowed site influences.

Stem bumps (nodal swellings) are a common defect in *P. patula*. Only 7% of the 5311 trees assessed on the 159 plots had completely smooth stems. 10% of all trees in mature stands had severe bumps. 23% of trees with bumps had bumps more strongly developed on the north to north-west side and to a lesser extent on the south side. These bumps were found exclusively in trees with eccentric pith and always on the side closest to the pith. Wind thus appears to play a role. Prediction models explained up to 61% of the variation in bumps development. The most severe bumps occurred on sites of medium to low altitude, high rainfall, wet soil climate, ridge top positions and near the Escarpment edge. These variables were considered to be related to stem stability and exposure, and thus susceptibility to wind stresses.

6.2 SITE RELATIONSHIPS

The modelling process identified site factors related to the growth, litter decomposition and wood properties of *P. patula* in the study area. From the evidence it is entirely plausible that many of these roles could be causal rather than merely statistical relationships in the strict sense of the word.

6.2.1 CLIMATIC FACTORS

6.2.1.1 Latitude and longitude

As expected, *latitude* had little influence on any of the parameters studied, as the difference between the latitudinal extremities of the study area was less than one degree. Due to the rapid increase in altitude from east to west, *longitude* was more strongly related to growth and other parameters, expressing a temperature effect. As *altitude* expressed this effect more strongly, however, *longitude* was regarded as having minimal influence.

6.2.1.2 Rainfall

Although *rainfall* did not appear in any of the *site index* models, the correlation coefficient (r = -0,48) indicated that a decrease in *site index* was associated with increasing *rainfall*. Apart from possible soil aeration effects, *rainfall* was found to be inversely related to soil *exchangeable bases*, *P* and *pH*, but directly related to *exchange acidity*, *Al* and *organic carbon*. It was also inversely related to foliar *Ca*. High rainfall appeared to retard the decomposition of litter. *Rainfall* was positively correlated with litter thickness (r = 0,56) and also appeared as a variable in litter prediction models, presumably affecting the activity of decay organisms by influencing aeration and temperature. Stem bumps increased in severity with increasing *rainfall*, which was an important predictor in the models. This relationship can probably be ascribed to decreased stem stability as a result of restricted root development in wet soil.

It is therefore apparent that the mean annual rainfall in some parts of the study area may be too high for *P. patula*, affecting as it does not only tree growth, but also litter decomposition and the incidence of stem bumps.

6.2.1.3 Temperature

Temperature, as expressed by *altitude*, was strongly related to tree growth, litter decomposition, wood density and stem bumps. The relationship between *site index* and *altitude* was curvilinear, with the optimum between 1200 and 1500 m. *P. patula* appears to be more sensitive to the cold environment at high altitude than to the warmer lower regions. Litter decomposition was severely retarded at high altitude. Decay organisms are apparently sensitive to the lower temperatures, especially when other environmental conditions (Model 4.4) are also unfavourable. Outer wood density decreased with decreasing temperature. *Altitude* was the most important variable for prediction of *outer density* (Model 5.2). The size and frequency of stem bumps were much less severe at high altitude. Trees at higher altitude are shorter (Fig. 2.9) and have a higher taper. This would result in stronger stems less susceptible to wind stresses and thus bump development. *Altitude* was the most important predictor of bump severity (Model 5.6).

6.2.1.4 Solar radiation

Aspect had no influence on any of the parameters studied. Only when it was combined in an *index of summer radiation* did it have a small influence on *site index* on the steepest slopes. Growth was slightly better on steep southerly slopes than on steep northerly slopes. Radiation indices for *winter* and *equinoxes* played no role. The conclusion is that radiation is not of great importance under the high rainfall conditions of the study area, a fact confirmed by studies elsewhere.

6.2.1.5 Wind

There are grounds for believing that wind may be the major cause of stem bumps:

(i) Bumps which were more strongly developed on one side of the stem were not randomly oriented but faced in specific compass directions.

(ii) Bumps were least severe at high altitude. As trees at high altitude are shorter and have a higher taper, stems would be stronger than at lower altitude.

(iii) Bumps were more severe under high rainfall and wet soil conditions. As root development is adversely affected by wet soil, stem stability could be reduced.

(iv) Bumps were more severe on ridge tops than on mid and lower slopes, and least severe on foot slopes. In this case *slope position* is probably an expression of exposure.

(v) Bumps were more severe on *Selati* substrate, the only category of *geology* to appear in models. As the Selati Formation is located along the exposed edge of the Escarpment, this could also indicate a wind effect.

(vi) Bumps increased in size with age. The tendency of *P. patula* to develop wide, heavy crowns with increasing age results in decreased stem stability.

If these factors can be accepted as being related to susceptibility to wind stresses, then it is likely that bumps are a response to these stresses at the zones of greatest weakness on the bole, viz. at the nodes, and in the lower part of the bole, where these stresses are strongest. A more appropriate term for stem bumps would thus be "crumples".

6.2.1.6 Other factors

Some of the soils of the study area may be sensitive to the effects of air pollution at the deposition rates currently being experienced in the Eastern Transvaal, which may also have implications for litter decay rates. This problem, as well as the possible increasing levels of CO_2 in the atmosphere, were outside the scope of the present study.

6.2.2 SOIL FACTORS

6.2.2.1 Nutrient elements

Nitrogen

Soil *N* was not determined, but foliar *N* did not appear to be related to *site index* or any of the other parameters studied. Although it was apparently a minor predictor in the litter model (Model 4.6), it accumulated in quantities of up to 3 tonnes per hectare in thick litter layers, with possible implications for continuous site productivity.

Phosphorus

Although Bray 2 extractable soil *P* levels were low, this was not reflected in foliar *P* levels which indicated that this element was well supplied. Support for this came from the low correlation between foliar *P* and *site index*, the absence of *P* from prediction models and the indication by a DRIS diagnosis of trees on a poor site that P was not deficient. The low correlation between foliar *P* and Bray 2 *P* may therefore indicate that Bray 2 was not the most appropriate extractant to use in this case. A further implication is that *P. patula* in the study area may be obtaining sufficient P from sources other than Bray 2 P, possibly from organic P. With the high organic carbon content of soils in the area (mean of 4,0%), it is possible that mineralization of organic P supplies most of the requirements. P evidently played no role in litter accumulation, but the amount of P in litter layers of average thickness greatly exceeded that in the underlying topsoil, the difference widening with increasing litter thickness. *P* played a role in predicting *8-year spirality* of wood, possibly as a general expression of site quality.

Potassium

K deficiencies are possible on some sites, as *K* appeared as a predictor of *site index* in both the soil and foliar models (Models 2.3, 3.1, 3.2). It did not, however, appear in the full model for prediction of *site index* (Model 2.6). Foliar *K* varied according to geological substrate, but in strong contrast to soil exchangeable *K*, foliar *K* was lowest on soils derived from dolomite. A high, negative correlation between foliar *K* and *Mn* suggests that uptake of K may be suppressed by high levels of Mn, which is extremely high in dolomite-derived soils. Of all nutrients the largest difference between litter and foliar nutrient concentrations was that for *K*. Litter *K* was much lower than foliar *K*, due either to internal translocation before litterfall or to rapid leaching from the litter. *K* was not, however, of importance in predicting *litter thickness*.

Calcium

Evidence suggests that Ca may be the most deficient nutrient in the area. It was the most important variable in the model to predict *site index* from soil analytical parameters (Model 2.3), and the only soil nutrient to appear in the full site model (Model 2.6). Exchangeable Ca in soils in the study area varied from 1 to 770 mg kg^{-1}. Its relationship with *site index* was logarithmic, with a possible critical level set at 200 mg kg^{-1}. Similarly *Ca* was the most important foliar nutrient (Model 3.1). As in the case of soil *Ca*, its relationship with *site index* was logarithmic, with a provisional critical level of about 0,25%. Also in the case of foliar nutrient ratios *Ca* was prominent, with the *Ca/Mg* ratio being the most important (Model 3.2). Still further evidence was obtained from a DRIS diagnosis run on trees from a randomly selected poor site, which indicated that Ca was the most limiting element. The highest correlation coefficient between soil and foliar nutrients was for *Ca*, suggesting that Ca is readily taken up by the needles. The highest correlation coefficient between foliar and litter nutrients was also for *Ca*, indicating that Ca is not readily translocated before litterfall. The highest correlation coefficient between litter and soil nutrients was for *Ca*, but in this case the reason was not apparent. As in the case of P, the difference between the amount of Ca in litter over 10 cm in thickness and that in the underlying topsoil was excessive. Litter *Ca* was correlated with *litter thickness* but did not appear in the prediction model (Model 4.6), possibly due to the dependencies among litter nutrients. *Ca* appeared in models to predict *8-year spirality* (Model 5.5) and *stem bumps* (Model 5.6). Its role in these cases was not clear, other than as a general expression of site quality. In both models the relationship with the dependent variable was logarithmic.

Magnesium

Mg was an important predictor in both the soil and foliar models (Models 2.3, 3.1, 3.2), having a logarithmic relationship with *site index*. However, in both the soil and foliar models the regression coefficients were negative. The question arises whether a relative oversupply of Mg is indicated, or whether the sign may be incorrect due to a small amount of multicollinearity in the models. There was some evidence in favour of the latter. *Mg* was absent from litter models, but appeared in the stem bumps model (Model 5.6), the role being uncertain.

Aluminium

Al was inversely related to *site index* in both the soil and foliar models (Models 2.3 and 3.1), but was not an important predictor. *Al* concentration in litter was not assessed. It appeared in the model to predict *inner wood density* (Model 5.1), but with a minor and uncertain role.

Boron

B was only assessed as a foliar nutrient. It was an important predictor in Models 3.1 and 3.2, but contrary to expectations this element was inversely related to *site index*. B deficiencies in other countries and species have often been reported, but no references could be found to any loss of growth resulting from a natural excess of B. Thick litter layers were associated with high foliar *B* levels (Model 4.5), but litter *B* was not assessed.

Copper

Foliar *Cu* appeared to reach very low levels on some sites, but it did not appear as a variable in any models.

Manganese

Mn was only assessed as a foliar nutrient. Although it did not appear in any models, there was some evidence that *site index* was depressed at foliar levels above 2000 mg kg^{-1}. These exceptionally high levels of *Mn* are a result of the presence of large residues of manganese wad in soils derived from dolomite, as well as from Timeball Hill in the vicinity of dykes and sills which have intruded through the dolomite. High soil *Mn* may suppress the uptake of *K*, as described above. There are also problems in particle size analysis (Appendix 7.1).

Other nutrients

No other nutrients appeared to have any relationships with tree parameters.

6.2.2.2 Other soil analytical parameters

Texture

Subsoil clay content was directly related to *site index* in the soil model (Model 2.3), probably due to its influence on cation exchange capacity. *Coarse sand* of the surface soil also appeared in Model 2.3 in a positive relationship with *site index*. Surface soils high in coarse sand tend to be better drained. In the full model (Model 2.6), however, these two variables were replaced by surface soil *fine sand*, in an inverse relationship with *site index*. Surface soils high in fine sand may be prone to compaction and crusting, and tend to be associated with wet sites.

Coarse sand of both the A and B horizons were important in predicting *litter thickness* (Model 4.2). The negative coefficient for the A horizon could imply better drainage, whereas the positive coefficient for the B horizon implies that litter accumulation may be enhanced by low nutrient status and poor sub-surface drainage. The log of *coarse sand, B horizon* was important in the prediction of *outer wood density* as well as of *density gradient* (Models 5.2, 5.4). An explanation is not apparent. *Total sand, B horizon* was important for the prediction of *8-year spirality*, again with no apparent explanation.

Acidity

Soil *pH in water* was more closely related to *site index* than was *pH in KCl* (Model 2.3). Variation in *litter thickness* was strongly associated with topsoil *exchange acidity* (Models 4.1, 4.3). As *litter pH* was more than one unit lower than *soil pH*, it was assumed that this was an effect rather than a cause of litter accumulation, but no proof of this was available. A similar uncertainty arose in the case of *litter pH*, which was strongly associated with *litter thickness* (Model 4.6). Either way, there could be important implications from the increased levels of atmospheric deposition of pollutants being experienced in the Escarpment area. *Exchange acidity* appeared in models to predict *outer wood density* and *density gradient* (Models 5.2 and 5.4), while *pH* was the most important predictor of *8-year spirality* (Model 5.5). The role of acidity in these models is unclear, but it could be related to a general expression of site quality.

Organic carbon

The only apparent role of *organic carbon* was in the prediction of *site index* from soil parameters (Model 2.3), but its influence was minor and probably related to its association with soils with a wet micro-climate.

6.2.2.3 Soil depth and stoniness

Effective rooting depth, defined as depth to at least 40% stones by volume, to saprolite, to a dense horizon, or to a wet horizon, whichever occurs closest to the surface, was an important site characteristic that appeared in all *site index* prediction models. Soil depth influences the availability of moisture and nutrients. The most important depth restriction proved to be a concentration of stones of more than 40% by volume. These stone layers appear to act as a barrier to the upward movement of moisture during the dry season, the surface soil having been dried out by evopotranspiration. The resulting temporary soil water deficit would restrict the uptake of nutrients by the surface feeding roots. Such stone layers occurred in nearly 50% of the soils surveyed, and were mostly within 50 cm of the surface. *Site index* was also associated with the *volume of stones* in the subsoil. Stones reduce the quantities of nutrients and moisture available to roots. *Litter thickness* was similarly influenced by *ERD*, which was an important predictor in Model 4.2. Shallow soils apparently cause seasonal conditions too dry for decay organisms to operate effectively. Some of the thickest litter layers were observed on shallow soils of the Glenrosa form. *ERD* and *volume of stones* were associated with variation in wood properties, but their role was uncertain.

6.2.2.4 Soil water

A number of site parameters which appeared in models were interpreted as being related to soil water regimes. These were *rainfall*, subsoil *hue*, topsoil *coarse sand*, and topsoil *fine sand*. The influence of high rainfall on soil properties was discussed in para 6.2.1.2 above. Increasing yellowness of the subsoil was regarded as indicating impaired drainage. Topsoils high in coarse sand tend to be better drained than topsoils with a high fine sand content which were found to be associated with the wetter sites.

Site index was found to be inversely related to *rainfall* (para. 6.2.1.2 above), subsoil *hue* (Model 2.10) and topsoil *fine sand* (Model 2.6). In several models *litter thickness* was directly related to *rainfall* and subsoil *hue*, but inversely related to topsoil *coarse sand*. The percentage of trees with *stem bumps* was related to *rainfall* and subsoil *hue* (Model 5.6) in the same manner as was *litter thickness*. Wet site conditions thus appear to be a problem for *P. patula*.

6.2.2.5 Topography

Topographic variables acted as surrogates for properties such as soil moisture, drainage, nutrients, soil depth, radiation and exposure. *Slope position* was an important variable in *site index* models. As its regression coefficients were larger in the field model (2.12) than in the full model (2.6), *slope position* appeared to partially express the effect of *calcium* in the case of the field model. *Slope position* was also a minor variable in models to predict *inner density* (Model 5.1) and *density gradient* (Model 5.4), probably as an expression of general site quality. In the case of *percentage of trees with bumps* (Model 5.6), *slope position* was regarded as an expression of exposure. *Slope gradient* appeared in some site index and wood properties models, probably as an expression of soil depth and solar radiation.

6.2.2.6 Geology

There are large differences in soil properties between geological substrates. These were described in Chapter 1. *Geology* was the most important predictor of *site index* by acting as a surrogate for many of these properties. Removal of *geology* as a variable from the models resulted in its substitution mainly by important soil nutrients, for which it thus appears to be a surrogate.

Although there were major differences between geological substrates, those of importance for tree growth were accounted for by other variables in the models, such as *altitude, effective soil depth, volume of stones* and subsoil *hue*.

Soil chemical differences between geological substrates were largely confirmed by foliar analyses. Foliar *Ca*, for example, was highest on *Granite* and *Dolomite*, and lowest on *Black Reef*, corresponding exactly with soil exchangeable *Ca*. An exception was *K*, the uptake of which may be suppressed by soil *Mn* on *Oaktree, Dolomite* and *Timeball*, the latter only in the presence of *Diabase*.

Geology was of less importance for the prediction of *litter thickness*. Only *Timeball* (thick litter layers) and *Dolomite* (thin litter) appeared in models. *Geology* had little influence on wood properties. Only in Model 5.6 did a single category, *Selati*, appear as a variable indicating severe development of *stem bumps* as a result of wind exposure.

6.2.2.7 Site index

Site index was the most important variable in models to predict *litter thickness* (Models 4.3, 4.4) . Acting as a probable surrogate for many variables expressing general site quality, *site index* influences the activity of micro-organisms responsible for the breakdown of litter. Similarly *site index* was the most important variable for the prediction of *inner wood density* and *density gradient* (Models 5.1, 5.4). Its absence from the model to predict *outer density* (5.2), which was more related to *altitude*, was in marked contrast.

6.2.3 STAND FACTORS

Stand conditions could have an important influence on some of the parameters studied and must therefore be regarded as environmental factors. *Age* was standardized at 20 years in the case of *site index* and thus played no role. Neither did *age* affect foliar nutrients within the sample range, viz. 29 to 47 years. It is not known why *age* was a predictor of *litter thickness* in Model 4.3 but not when soil acidity variables were removed (Model 4.4). Wood *density* and *spirality* were investigated at predetermined ages, but *stem bump size* was found to increase with stand *age*. *Stand density* was not related to any of the parameters studied. In the case of *litter thickness* prediction, this was a confirmation of a previous study by the author. The fact that wood density parameters were not related to *stems per hectare* lent some support to Turnbull's theories (Turnbull and Du Plessis, 1946; Turnbull, 1947). In the case of *stem bumps* a possible explanation is that although widely spaced trees would have greater stem stability (higher taper), this effect is neutralized by the heavier branching of the crowns, rendering these stems as unstable as those with smaller crowns and lower taper in stands of higher density.

From the records *seed source* appeared to be an unlikely source of variation. The success of the site index models would tend to support this viewpoint.

6.3 IMPLICATIONS FOR RESEARCH

6.3.1 SITE DESCRIPTION

1. The geological substrates identified as important in the study area could form the basis for a forest land type classification. *Geology* accounted for the greatest variation in *site index*, and boundaries are fairly easily determined. A subdivision of *Granite* into an upper and a lower zone (Ch 1, para 1.3.1), however, might be necessary. Recognition of these land types is essential for a variety of research purposes such as surveys for vegetation (e.g. weeds, natural vegetation), regeneration, harvesting, for hydrology, and for the selection of representative sites for field experiments in provenance, progeny, fertilizer, establishment and other research. The documented differences in soil properties should be particularly useful in nutrition research.

2. The 439 plots used in the site survey are representative of the afforested area. As such they can be regarded as benchmark sites, i.e. a potential source of data for a variety of research purposes, e.g. nutrition (P-retention, P-extractants, sources of P), further site studies, and monitoring of soil changes possibly resulting from management practices and air pollution. A large data bank is immediately available, and the location of plots has been described and mapped should collection of new data be necessary.

6.3.2 SOIL PROPERTIES AND FOLIAR NUTRIENTS

1. As the curve for *site index* on *effective rooting depth* is still increasing at *ERD* = 150 cm (Fig. 2.7), a depth of 1,5 m for soil pits is probably insufficient for this type of study. Pits should in future be dug to a suggested 2 m to determine the approximate maximum depth utilized by *P. patula* roots.

2. Less subjective methods are still required to identify restrictions in the determination of *effective rooting depth*. The interaction between depth to stone layer and both the induration and thickness of stone layers should be studied. Suitable parameters to express drainage and the degree of wetness of a soil horizon are necessary.

3. Further research is necessary on the influence of slope position on tree growth. Catena surveys of soil depth, nutrients and moisture regimes across representative slope profiles on the different landtypes would serve to explain the importance of slope units and assist in identifying these units less subjectively.

4. As it has been shown that *P. patula* obtains most of its nutrients from the topsoil, more attention should be given to A horizon than B horizon nutrient elements.

5. Bulk soil samples from the surface of well-chosen plots are unnecessary in the area. A bulk sample taken from the sides of a single soil pit dug in the centre of the plot is all that is required.

6. Laboratory accuracy in the analysis of soil samples is of crucial importance in site research. The standards of commercial laboratories appear to be inadequate for the purpose.

7. Standard procedures for particle size analysis cannot be used for soils from Oaktree, Dolomite and Timeball parent materials, due to the high concentrations of manganese. Ultrasonic dispersion has proved to be an acceptable alternative.

8. As calcium has emerged as the most deficient element in the nutrition of *P. patula*, priority should be given to this element in nutritional research.

9. Research is required on the sources of phosphorus in the nutrition of *P. patula*.

10. Confirmation is required that Mg is generally deficient rather than in oversupply.

11. The role of Mn in apparently suppressing the uptake of K requires research.

12. Possible copper deficiencies should be investigated.

13. The apparent oversupply of B requires confirmation.

6.3.3 LITTER

1. There is some urgency in the need to determine whether excessive accumulation of litter is a threat to the maintenance of site productivity or not. This can be revealed by research on acidification processes in the litter and on nutrient cycling to determine the degree of nutrient immobilization in litter. This research would have to include the possible cumulative effects of atmospheric pollution on litter dynamics.

2. Should excessive litter accumulation prove harmful, the dividing line between the positive and negative roles of litter would need to be determined along with reasons for the change in these roles.

3. Decomposition processes, including the role of micro-organisms, mycorrhizae and fine roots, require research. Factors possibly influencing accumulation rates which were not investigated in the present study include lignin content, C/N ratio, aluminium content and site variation in litterfall rates.

4. Strategies to ensure representative sampling of the extremely variable litter layers require attention.

5. Methods for reduction of litter layers by speeding up decomposition processes, e.g. through application of phospho-gypsum and other fertilizers should be researched.

6. The observed phenomenon of *litter thickness* being inversely proportional to *site index* in the Transvaal but directly proportional to *site index* in the Cape, even for the same species, requires research.

6.3.4 WOOD PROPERTIES

1. Between-tree variation reduced the accuracy of *wood density* and *spirality* models. This problem is fairly insurmountable. The only prospect of obtaining adequate information on the role of site is by investigation of clonal material on a variety of sites. On the other hand the potential for genetic improvement with regard to wood properties is considerable.

2. The role of density gradient is still not clear and requires further

research.

3. Sampling for spirality needs to be done at an early age as spirality decreases with age.

4. Experimental verification of the causes of stem bumps presents feasibility problems. Confirmation of the effect of stand density, however, could be obtained from an assessment of stem bumps in C.C.T. spacing experiments. In the meantime it can be accepted that wind is probably the major cause.

5. Genetic variation in the severity of bumps is probably sufficient to achieve success in a tree improvement programme, which is probably the only effective way of solving this problem.

6. The implications for tree improvement are that differences in wood properties are not all genetic. Site effects must be taken into consideration in progeny testing, for example selection of bump-free phenotypes is no guarantee that their progeny will also be clean-stemmed, unless the parent trees were selected from sites prone to severe bump development. Breeding for clean-stemmed trees will require progeny testing on sites prone to severe bump development. Such sites can be identified by use of the prediction model.

6.3.5 REGRESSION ANALYSIS

1. Part of the accuracy of the site index models was probably due to the stem analysis method of determining tree height at 20 years, and this method is to be recommended for any future studies. On the other hand, the relationship between *site index* and *volume* is only approximate, and other parameters require investigation.

2. For determination of mean tree height, a minimum of ten trees is recommended.

3. A blind, mechanical application of existing statistical procedures is not likely to produce a good model. A practical, commonsense approach is essential, bearing in mind that what is uncovered along the way to the formulation of an equation may often be as valuable and as informative as the final equation itself.

4. Non-linear relationships are not always revealed by residual plots or scatter diagrams.

5. Non-quantitative variables should always be expressed in dummy variable format for regression analysis.

6. Best-subsets regression analysis is preferable to any of the stepwise methods when there are a large number of independent variables, for a variety of reasons.

7. In cases of doubt, there appears to be no objective method of determining whether the sign of a regression coefficient is correct or not.

8. When a regression coefficient has the wrong sign as a result of a small degree of multicollinearity in the model, ridge regression should be used to adjust the coefficients.

9. Outliers and points which fit the model badly require careful, and if necessary, repeated investigation regardless of what is involved. Although this increases the cost of model construction, it is an essential step in the quest for the best model.

10. Model validation is essential.

11. Other multivariate techniques may produce better results than regression analysis, and these possibilities require consideration.

6.3.6 MODELS

1. The field model (Model 2.12) has been shown to be satisfactory for practical use, and site mapping with the parameters in the model is all that is required. Adjustments will have to be made to accommodate genetic gain resulting from tree improvement, new provenances, etc.

2. The parameters in Model 2.12 should be used as guidelines in the determination of site uniformity in the selection of sites for field experiments in whatever discipline.

3. Some of the site models have potential for extrapolation to regions outside, but close to, the study area, and should be tested with this end

in view. With little extra effort, site models can be developed for surrounding areas, e.g. the Timeball Hill shale zone south-west of the study area.

4. Models for *P. taeda* and *P. elliottii* should be constructed from the data already accumulated, to achieve the ultimate objective of species-site allocation on a scientific basis.

5. Foliar nutrient models have shown that certain nutrients are associated with *site index* at 20 years, regardless of tree age above 20 years. The DRIS system holds promise for the diagnosis of nutrient problems and the provisional norms require testing in fertilizer trials as a matter of priority. A DRIS data bank should be established and augmented continually.

6. Both the litter and stem bumps models are sufficiently accurate for use in site classification.

6.4 IMPLICATIONS FOR MANAGEMENT

6.4.1 GEOLOGY

1. Geology has been shown to be the best indicator of site differences in the region. The geological substrates identified as important could form the basis for a forest land type classification which can be used to differentiate sites broadly in terms of altitude, rainfall, topography, soil drainage, erosion, effective rooting depth, soil texture, compaction hazard, stoniness, soil nutrients and other properties. *Geology* was responsible for differences in mean *site index* for *P. patula* of up to 7 m. There are also differences in species composition and intensity of competition of weed growth, although this has not yet been documented. Similarly differences in survival of transplants can be expected and it is likely that fertilizer response will also differ. A geological map on a scale of 1: 125 000 was compiled. Geological substrates are rated for some selected properties in Table 6.1.

Table 6.1 Ranking of *geology* for some selected properties, from 1 = low, to 6 = high. (Based on prediction models and data from 439 representative sites).

Property	*Granite*	*Selati*	*Black Reef*	*Oaktree*	*Dolomite*	*Timeball*
Site index	6	3	1	3	5	4
ERD	6	3	6	6	6	1
Soil stoniness	2	4	1	1	2	6
Clay + silt content	4	3	1	5	6	5
Compaction hazard	1	2	3	4	1	1
Slope steepness	3	2	1	1	2	6
Altitude	1	5	4	3	3	6
Rainfall	1	6	5	3	1	3
Soil available P	6	5	5	1	2	5
Exch. bases	5	2	1	1	6	2
Litter accumulation	-	-	-	-	1	6
Stem bumps	-	6	-	-	-	-

2. For most purposes *Diabase* can be ignored as a landtype unit, but will have to be considered if ripping is applied to break the stone layer covering the subsoil.

6.4.2 SITE INDEX PREDICTION

1. The field model (Model 2.12) predicted *site index* (30% top height at 20 years) of *P. patula* on 20 validation plots within a mean of 0,36 m on average sites. Site index is usually highly correlated with the volume yield of stands with the same thinning regimes. Although the calculations can be made in the field using a pocket calculator, it is simpler to use the available computer programme. The precision of the model depends largely on the accuracy with which the site parameters are assessed, some of which are difficult to evaluate without experience and training.

2. Although the model is accurate on average sites, there may be some atypical ones which were not sampled and on which predictions would be less accurate. The model should be tested in cases of doubt. The model should not be used outside the defined study area without testing, but it does have potential in surrounding areas such as the Timeball shales west of Nelspruit.

3. The model will, at various stages in the future, have to be updated to make provision for possible genetic gain resulting from the improvement programme.

4. A model for the prediction of site index at 30 years can be made available with minimum effort.

5. The site requirements of *P.patula* in the defined area have been identified. Key site factors have been identified. Knowledge of site factors having less influence can be equally important, and these have also been identified, e.g. *aspect*.

6. Effective rooting depth for *P. patula* has been defined. Even well-weathered saprolite, for example, cannot be taken into consideration when assessing this parameter. For model use, ERD must be assessed to 1,5 m depth. Generally, stony soils are not suitable for *P. patula*.

7. Stone layers with a volume of stones exceeding 40% severely restrict tree growth if they occur within 50 cm of the soil surface. There is thus a strong case for ripping where feasible, as this should result in a permanent improvement in site productivity. According to Fig. 2.6.3, ripping of a soil with a restrictive stone layer at 30 cm depth can

be expected to result in an improvement in site index of approximately 4 m on an average site. The same would apply in the case of a dense soil horizon at the same depth.

6.4.3 THE LITTER PROBLEM

1. Although experimental evidence is not yet available, there are strong indications that thick, undecomposing litter layers are a potential threat to the continuous productivity of such sites. Establishment problems have already been experienced. Other potential problems include the acidification of runoff water, with implications, for example, for fish culture. Litter problems are likely to be aggravated by air pollution. Support for research into the litter problem is therefore necessary.

2. Burning of thick litter layers is not usually successful and in any case would remove large quantities of nitrogen immobilized in the litter (Table 4.12).

3. There are more nutrients in even moderately thick litter layers than in the underlying topsoil. Removal of litter for sale to nurseries would therefore have more serious consequences than removal of the topsoil.

4. Pending research into methods of accelerating decomposition, the best solution would be to use the litter model (Model 4.4) to identify sites likely to accumulate litter, and regenerate with species other than *P.patula*.

6.4.4 WOOD PROPERTIES

1. The density and spirality models were not sufficiently accurate for practical use other than to indicate the following general guidelines:

   (i) For sawlog production outer density is of greater importance than inner density. As outer density is lower at high altitude, better quality sawlogs will be produced at medium to low altitude.

   (ii) Spirality is higher on poor sites.

(iii)For pulpwood production inner density is of greater importance. This is affected mostly by soil conditions. Poor sites will produce higher quality pulpwood. As spirality would also be higher on such sites, sawlog quality would be adversely affected.

2. The stem bumps model (Model 5.6) on the other hand is sufficiently accurate for practical use. As the recovery of sawn timber from bumpy trees is reduced and as approximately 10% of mature stands had excessive bumpiness, the problem requires attention. The model can be used to identify sites likely to produce trees with a severe bumps problem. Such sites should either be regenerated with alternative species or the rotation shortened (smaller bump size). This problem has not, as yet, been addressed in the tree improvement programme.

6.4.5 SITE CLASSIFICATION

The realities of the timber supply situation will eventually dictate the essential use of site classification and Geographic Information Systems (G.I.S.) for species-site allocation, site-specific silviculture and other means to increase productivity and improve management. Most of the parameters in the models can be easily mapped and incorporated into a G.I.S. Although the models can be applied on an *ad hoc* basis for prediction purposes on specific sites, surveys of large areas would be more accurate and cost-effective. For example, stereoscope mapping of slope positions would be more efficient than point sampling in the field. Ground-penetrating radar may eventually prove feasible in mapping ERD, especially as stone layers are the major restriction factor. Until site relationships for other species can be modelled, Model 2.12 can already be used to estimate the potential of *P. patula* on sites currently planted to other species.

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APPENDIX 1 PROFILE DESCRIPTIONS AND ANALYTICAL DATA FOR MODAL SOILS ON EACH GEOLOGICAL SUBSTRATE.

1.1 Granite

FORESTRY SOIL PROFILE DESCRIPTION

PROFILE NO. E21	REGION WILGEBOOM	LOCALITY Compt A61	PURPOSE Site factor survey	DATE 14-10-77	SURVEYOR G. N. Schafer
SOIL FORM HUTTON	MACRO LANDFORM	GEOLOGY (HARD ROCK) GROUP GRANITE		PARENT MATERIAL DEPOSITION	
SOIL SERIES FARNINGHAM	TERRAIN UNIT Lower mid				
SOIL PHASE	MICRO RELIEF	FORMATION		LITHOLOGY	
DRAINAGE Good	MOISTURE M	SLOPE SHAPE Convex	ANGLE 14 %	MEMBER	HARDNESS
WATER TABLE		ASPECT 300°			RIPABLE ?
E.R.D. 150 cm		ALTITUDE 922 m		SURFACE ROCK TYPE –	COVER / DISTRIBUTION
EROSION HAZARD		LITTER DEPTH / HUMUS TYPE		VEGETATION AND LAND USE	
TRAFFICABILITY		01 30 mm; 02 2 mm		P. elliottii Age 38	

HORIZON/TYPE		Orth. A1	R.Ap A3	R.Ap B21	R.Ap B22
LIMITS/MOISTURE (cm)		0–16 D	16–36 M	36–90 M	90–(150) M
MUNSELL COLOUR	MOIST	5YR 3/4	2,5YR 3/4	2,5YR 4/6	10R 3/6
	DRY				
TEXTURE	% CLAY	27	28	43	44
	SANDGRADE	Coarse	Coarse	Coarse	Coarse
	CLASS	SCL	SCL	SC	SC
STRUCTURE	GRADE	Weak	Apedal	Ap.	Ap.
	SIZE	Medium			
	TYPE	Sub. & blocky	Porous	porous	porous
CONSISTENCE	DRY	Slightly hard			
	MOIST		V. friable	V. friable	V. friable
	WET				
PERMEABILITY		Rapid	Rapid	Rapid	Rapid
VOIDS	FREQUENCE				
	SIZE				
	TYPE				
MOTTLES	FREQUENCE				
	SIZE				
	CONTRAST				
	CAUSE				
	COLOUR				
	FORM				
CUTANS	FREQUENCE	many	many	common	many
	COLOUR	dk. brown	red brown	brown	red brown
	TYPE	organic	organic	organic	organic
	LOCATION	Throughout	throughout	throughout	root channels
NODULES	FREQUENCE				
	SIZE				
	HARDNESS				
	TYPE				
COARSE FRAGMENTS	FREQUENCE	5–15%	5–15%	5–15%	0–5%
	SIZE	<10 mm	<10 mm	<10 mm	<10 mm
	SHAPE	A	A	A	A
	TYPE	quartz	qtz	qtz	qtz
ROOTS	FREQUENCE	4 3	3 2	3 2	3 2
	SIZE	F M	F M	F M	F M
	DISTRIBUTION				
BOUNDARY	CONTRAST	clear	clear	clear	not reached
	TOPOGRAPHY	smooth	smooth	smooth	" "
SAMPLE NO.		E21 (A1)	E21 (A3)	E21 (B21)	E21 (B22
REMARKS					

APPENDIX 1 (cont'd)

1.1 **Granite** (cont'd)

Profile No. E21

ANALYTICAL DATA

	units	A 1	B 21
Clay	g 100 g^{-1}	27	43
Silt	"	14	6
Sand	"	59	51
Fine sand	"	11	9
Medium sand	"	14	11
Coarse sand	"	34	31
Organic C	%	2,72	-
pH (H_2O)		4,85	5,25
pH (KCl)		4,20	5,45
Exch. acidity	cmol(+) kg^{-1}	0,97	0,06
P	mg kg^{-1}	5	2
K	"	21	5
Ca	"	73	13
Mg	"	31	15
Al	cmol(+) kg^{-1}	0,07	0,01
K + Ca + Mg 100 g^{-1} clay	index	2,49	0,47

APPENDIX 1 (cont'd)

1.2 Selati

FORESTRY SOIL PROFILE DESCRIPTION

PROFILE NO. P111	REGION BLYDE	LOCALITY Compt B26	PURPOSE Site Factor Survey	DATE 27/10/77	SURVEYOR G.N. Schafer
SOIL FORM GLENROSA	MACRO LANDFORM		GEOLOGY (HARD ROCK) GROUP WOLKBERG	PARENT MATERIAL DEPOSITION Binary Colluvial, in situ	
SOIL SERIES SAINTFAITHS	TERRAIN UNIT Ridge top		FORMATION SELATI	LITHOLOGY QTZT, SHL	
SOIL PHASE	MICRO RELIEF		MEMBER	HARDNESS	RIPABLE ?
DRAINAGE Good	MOISTURE M	SLOPE SHAPE straight	ANGLE 7%		
WATER TABLE –		ASPECT 320°			
E.R.D. 25 cm		ALTITUDE 1540m		SURFACE ROCK TYPE	COVER / DISTRIBUTION
EROSION HAZARD		LITTER DEPTH / HUMUS TYPE		VEGETATION AND LAND USE P. patula. Age 44	
TRAFFICABILITY		01 180 mm; 02 –			

HORIZON/TYPE	Orthic A1	Litho B21	C1	C2	
LIMITS/MOISTURE (cm)	0 – 10 M	10 – 35 M	35 – 70 M	70 → M (150)	
MUNSELL COLOUR MOIST	5YR 2,5/1	5YR 2,5/2	Yellow	Red	
MUNSELL COLOUR DRY					
TEXTURE % CLAY	36	38			
TEXTURE SANDGRADE	F	F			
TEXTURE CLASS	SC	SC			
STRUCTURE GRADE	apedal	weak	Saprolite (quartzite). Soft	Saprolite (shale). Soft	
STRUCTURE SIZE		m			
STRUCTURE TYPE	porous	sub-blocky			
CONSISTENCE DRY					
CONSISTENCE MOIST	Very friable	friable			
CONSISTENCE WET					
PERMEABILITY	mod. rapid	rapid			
VOIDS FREQUENCE					
VOIDS SIZE					
VOIDS TYPE					
MOTTLES FREQUENCE					
MOTTLES SIZE					
MOTTLES CONTRAST					
MOTTLES CAUSE					
MOTTLES COLOUR					
MOTTLES FORM					
CUTANS FREQUENCE	many	many			
CUTANS COLOUR	black	dark brown			
CUTANS TYPE	organic	organic			
CUTANS LOCATION	throughout	throughout			
NODULES FREQUENCE					
NODULES SIZE					
NODULES HARDNESS					
NODULES TYPE					
COARSE FRAGMENTS FREQUENCE	0	70%			
COARSE FRAGMENTS SIZE		20 – 30 mm			
COARSE FRAGMENTS SHAPE		S-A X			
COARSE FRAGMENTS TYPE		QTZ, SHL			
ROOTS FREQUENCE	5 5	5 5			
ROOTS SIZE	F M	F M			
ROOTS DISTRIBUTION					
BOUNDARY CONTRAST		clear			
BOUNDARY TOPOGRAPHY		undulating			
SAMPLE NO.	P111 (A1)	P111 (B21)			

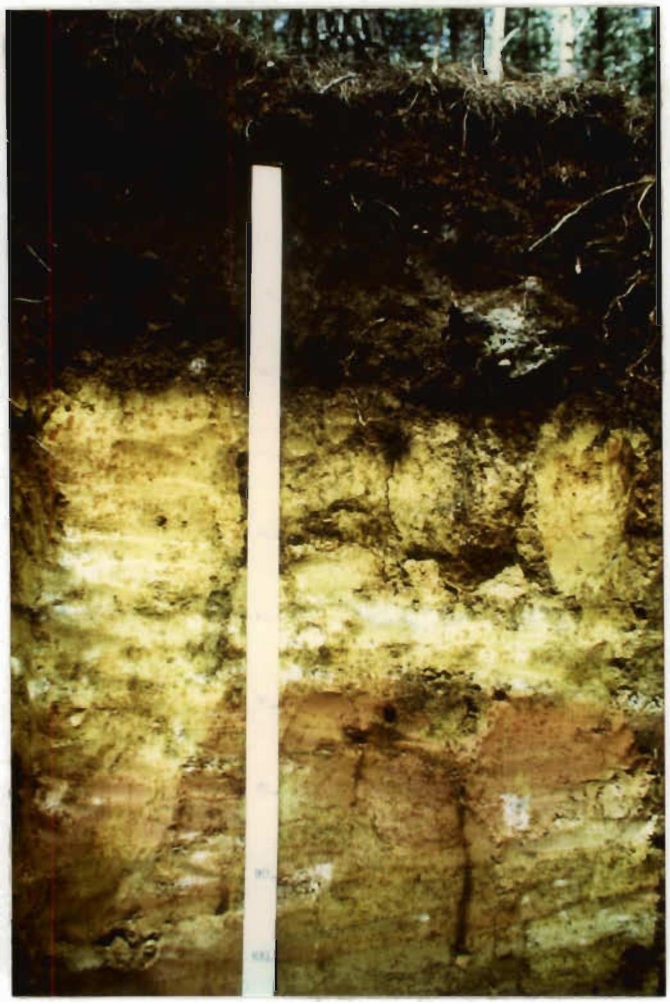
REMARKS

Stoneline in B21

APPENDIX 1 (cont'd)

1.2 **Selati** (cont'd)

Profile No. P111



ANALYTICAL DATA

	units	A 1	B 21
Clay	g 100 g^{-1}	36	38
Silt	"	10	10
Sand	"	54	53
Fine sand	"	34	31
Medium sand	"	10	10
Coarse sand	"	10	12
Organic C	%	7,76	-
pH (H_2O)		4,00	4,55
pH (KCl)		3,83	4,10
Exch. acidity	cmol(+) kg^{-1}	3,09	2,40
P	mg kg^{-1}	8	14
K	"	53	47
Ca	"	16	22
Mg	"	16	14
Al	cmol(+) kg^{-1}	1,50	0,83
K + Ca + Mg 100 g^{-1} clay	index	0,96	0,91

APPENDIX I (cont'd)

1.3 Black Reef

FORESTRY SOIL PROFILE DESCRIPTION

PROFILE NO. T87	REGION MAC MAC	LOCALITY Compt D96	PURPOSE SFS
DATE 8/76	SURVEYOR G.N. Schafer		
SOIL FORM HUTTON	MACRO LANDFORM	GEOLOGY (HARD ROCK) GROUP WOLKBERG	PARENT MATERIAL DEPOSITION Colluvial Binary / In situ
SOIL SERIES KYALAMI	TERRAIN UNIT lower mid	FORMATION BLACK REEF	LITHOLOGY QTZT
SOIL PHASE	MICRO RELIEF	MEMBER	HARDNESS
DRAINAGE Good	MOISTURE D	SLOPE SHAPE straight	ANGLE 13%
WATER TABLE —	ASPECT 20°		RIPABLE ?
E.R.D. 150 cm	ALTITUDE 1342 m	SURFACE ROCK TYPE	COVER / DISTRIBUTION
EROSION HAZARD	LITTER DEPTH / HUMUS TYPE	VEGETATION AND LAND USE P. taeda, Age 40	
TRAFFICABILITY	01 40 mm; 02 60 mm		

HORIZON/TYPE		Orthic A1	Orthic A3	R.ap. B21	R.ap. B22	Sapr. C
LIMITS/MOISTURE (cm)		0–14 D	14–30 D	30–60 D	60–105 D	105→(150) M
MUNSELL COLOUR	MOIST	5YR 2,5/2	5YR 3/2	5YR 3/2	5YR 3/2,5	2,5YR 4/6
	DRY					
TEXTURE	% CLAY	11	11	10	11	15
	SANDGRADE	C	C	C	C	C
	CLASS	SL	SL	SL	SL	SCL
STRUCTURE	GRADE	Aped.	Aped.	Aped.	Aped.	Aped.
	SIZE					
	TYPE	single grain	S.G.	S.G.	S.G.	porous
CONSISTENCE	DRY	loose	soft	soft	soft	friable
	MOIST					
	WET					
PERMEABILITY		mod.	rapid	rapid	rapid	rapid
VOIDS	FREQUENCE					
	SIZE					
	TYPE					
MOTTLES	FREQUENCE					
	SIZE					
	CONTRAST					
	CAUSE					
	COLOUR					
	FORM					
CUTANS	FREQUENCE	common	common	common	common	common
	COLOUR	YBr	Br	Dk.Br	R-Br	Dk-Br
	TYPE	organic	organic	organic	organic	organic
	LOCATION					
NODULES	FREQUENCE			V. few	V. few	V. few
	SIZE			medium	m	m
	HARDNESS			soft	soft	soft
	TYPE			I.C.	I.C.	I.C.
COARSE FRAGMENTS	FREQUENCE					
	SIZE					
	SHAPE					
	TYPE					
ROOTS	FREQUENCE	5 5	5 5	4 2	4 2	2
	SIZE	f m	f m	f m	f m	f
	DISTRIBUTION					
BOUNDARY	CONTRAST	clear	gradual	gradual	gradual	
	TOPOGRAPHY	undulating	und.	und.	und.	
SAMPLE NO.		T87 (A1)	T87 (A3)	T87 (B21)	T87 (B22)	T87 (C)

REMARKS

Rodent nest

APPENDIX 1 (cont'd)

1.4 Oaktree

FORESTRY SOIL PROFILE DESCRIPTION

PROFILE NO. E178	REGION MAC MAC / LOCALITY Compt. F3a	PURPOSE SFS	DATE 5/78 / SURVEYOR G.N. Schafer
SOIL FORM GRIFFIN	MACRO LANDFORM	GEOLOGY (HARD ROCK) GROUP CHUNIESPOORT	PARENT MATERIAL DEPOSITION colluvium
SOIL SERIES GRIFFIN	TERRAIN UNIT Ridge top		
SOIL PHASE	MICRO RELIEF	FORMATION OAKTREE	LITHOLOGY Shale
DRAINAGE Poor / MOISTURE M	SLOPE SHAPE convex / ANGLE 3%		HARDNESS
WATER TABLE –	ASPECT 5°	MEMBER	RIPABLE ?
E.R.D. 70 cm	ALTITUDE 1277	SURFACE ROCK TYPE	COVER / DISTRIBUTION
EROSION HAZARD	LITTER DEPTH / HUMUS TYPE	VEGETATION AND LAND USE P. elliottii. Age 31 yrs.	
TRAFFICABILITY	01 60mm / 02 —		

HORIZON/TYPE		Orthic A1	YBA B21	B22	R.ap. B23	
LIMITS/MOISTURE (cm)		0–25 M	25–40 M	40–55 M	55–(150) M	
MUNSELL COLOUR	MOIST	10YR 3/3	7.5YR 4/4	6.75YR 5/5	10R 4/6	
	DRY					
TEXTURE	% CLAY	48	46	50	55	
	SANDGRADE	F	C	C	C	
	CLASS	C	C	C	C	
STRUCTURE	GRADE	weak	apedal	ap.	ap.	
	SIZE	medium				
	TYPE	sub. & blocky	porous	porous	porous	
CONSISTENCE	DRY					
	MOIST	friable	v. friable	v. fr.	v. fr.	
	WET					
PERMEABILITY						
VOIDS	FREQUENCE					
	SIZE					
	TYPE					
MOTTLES	FREQUENCE					
	SIZE					
	CONTRAST					
	CAUSE					
	COLOUR					
	FORM					
CUTANS	FREQUENCE	common	many	many	many	
	COLOUR	D-Br	Y-Br	R.Br	R.	
	TYPE	organic	org.	org.	clayskins	
	LOCATION	throughout	t.	t.	t.	
NODULES	FREQUENCE					
	SIZE					
	HARDNESS					
	TYPE					
COARSE FRAGMENTS	FREQUENCE				70%	
	SIZE				20–250 mm	
	SHAPE				S-R, round	
	TYPE				SHL, Mn, DIA.	
ROOTS	FREQUENCE	6 6	3 1	2 1	2 1	
	SIZE	f m	f m	f m	f m	
	DISTRIBUTION					
BOUNDARY	CONTRAST	clear	gradual	gradual		
	TOPOGRAPHY	smooth	smooth	smooth		
SAMPLE NO.		E178(A1)	E178(B21)	E178(B22)	E178(B23)	
REMARKS						

APPENDIX 1 (cont'd)

1.4 **Oaktree** (cont'd)

Profile No. E178

ANALYTICAL DATA

	units	A 1	B 21
Clay	g 100 g^{-1}	48	46
Silt	"	19	22
Sand	"	34	32
Fine sand	"	25	16
Medium sand	"	7	7
Coarse sand	"	2	9
Organic C	%	6,63	-
pH (H_2O)		4,80	5,85
pH (KCl)		4,20	4,90
Exch. acidity	cmol(+) kg^{-1}	0,99	0,11
P	mg kg^{-1}	1	1
K	"	31	7
Ca	"	27	5
Mg	"	14	2
Al	cmol(+) kg^{-1}	0,27	0,18
K + Ca + Mg 100 g^{-1} clay	index	0,44	0,33

APPENDIX 1 (cont'd)

1.5 Dolomite

FORESTRY SOIL PROFILE DESCRIPTION

PROFILE NO. P158	REGION	LOCALITY Mac Mac C26a	PURPOSE SFS	DATE 5/78	SURVEYOR G.N. Schafer
SOIL FORM HUTTON	MACRO LANDFORM	GEOLOGY (HARD ROCK) GROUP CHUNIESPOORT	PARENT MATERIAL DEPOSITION Colluvial		
SOIL SERIES FARNINGHAM	TERRAIN UNIT Foot slope				
SOIL PHASE	MICRO RELIEF	FORMATION LYTTELTON	LITHOLOGY DOLOMITE		
DRAINAGE Good	MOISTURE M	SLOPE SHAPE Concave	ANGLE 6 %	HARDNESS	
WATER TABLE —	ASPECT N	MEMBER	RIPABLE ?		
E.R.D. 150 cm	ALTITUDE 1380 m	SURFACE ROCK	TYPE	COVER	DISTRIBUTION
EROSION HAZARD	LITTER DEPTH / HUMUS TYPE	VEGETATION AND LAND USE			
TRAFFICABILITY	01 50 mm; 02 —	P. patula Age 44			

HORIZON/TYPE		Orthic A1	B1	R. Ap. B21	R. Ap. B22	
LIMITS/MOISTURE (cm)		0–15 M	15 – 30 M	30 – 90 M	90 –(150) M	
MUNSELL COLOUR	MOIST	5YR 3/4	5YR 4/3	5YR 4/8	2,5YR 3/6	
	DRY					
TEXTURE	% CLAY	41	41	55	55	
	SANDGRADE	C	C	C	C	
	CLASS	Clay	Clay	Clay	Clay	
STRUCTURE	GRADE	weak	aped.	ap.	ap.	
	SIZE	fine				
	TYPE	sub-A-blocky	porous	porous	porous	
CONSISTENCE	DRY					
	MOIST	friable	v. friable	v. friable	v. friable	
	WET					
PERMEABILITY		mod. rapid	rapid	rapid	rapid	
VOIDS	FREQUENCE					
	SIZE					
	TYPE					
MOTTLES	FREQUENCE					
	SIZE					
	CONTRAST					
	CAUSE					
	COLOUR					
	FORM					
CUTANS	FREQUENCE	many	many	common	many	
	COLOUR	Br	R-Br	RBr	D-R-Br	
	TYPE	Organic	org.	org.	org.	
	LOCATION	ped faces	throughout	throughout	throughout	
NODULES	FREQUENCE					
	SIZE					
	HARDNESS					
	TYPE					
COARSE FRAGMENTS	FREQUENCE			<5%	<5%	
	SIZE			20–100mm	20–100mm	
	SHAPE			sub-A	sub-A	
	TYPE			Sh	Sh	
ROOTS	FREQUENCE	5 4	3 2	3 1	2	
	SIZE	f m	f m	f m	f	
	DISTRIBUTION					
BOUNDARY	CONTRAST	clear	gradual	gradual		
	TOPOGRAPHY	undulating	smooth	smooth.		
SAMPLE NO.		P158(A1)	P158(B1)	P158(B21)	P158(B22)	
REMARKS						

APPENDIX 1 (cont'd)

1.6 Timeball Hill

FORESTRY SOIL PROFILE DESCRIPTION

PROFILE NO. T59	REGION Ceylon	LOCALITY Compt F45	PURPOSE SFS	DATE 8/76	SURVEYOR G.N. Schafer
SOIL FORM HUTTON	MACRO LANDFORM		GEOLOGY (HARD ROCK) GROUP PRETORIA	PARENT MATERIAL DEPOSITION colluvial	
SOIL SERIES FARNINGHAM	TERRAIN UNIT Ridge top				
SOIL PHASE	MICRO RELIEF		FORMATION TIMEBALL HILL	LITHOLOGY shale	
DRAINAGE Good	MOISTURE M	SLOPE SHAPE convex	ANGLE 16%	HARDNESS	
WATER TABLE	ASPECT 40°		MEMBER	RIPABLE ?	
E.R.D. 15 cm	ALTITUDE 1555		SURFACE ROCK TYPE	COVER	DISTRIBUTION
EROSION HAZARD	LITTER DEPTH / HUMUS TYPE		VEGETATION AND LAND USE		
TRAFFICABILITY	01 50mm	02 30mm	P. taeda. Age 38		

HORIZON/TYPE	Orthic A1	R.Ap. B21	R.Ap. C		
LIMITS/MOISTURE	0 – 15 D	15 – 90 M	90 – (150) M		
MUNSELL COLOUR MOIST	2,5YR 3/4	2,5YR 3/6	2,5YR 3/4		
MUNSELL COLOUR DRY					
TEXTURE % CLAY	36	39	39		
TEXTURE SANDGRADE	FS	FS	FS		
TEXTURE CLASS	CL	CL	CL		
STRUCTURE GRADE	Apedal	aped.	aped		
STRUCTURE SIZE					
STRUCTURE TYPE	Porous	porous	porous		
CONSISTENCE DRY	soft				
CONSISTENCE MOIST		friable	very friable		
CONSISTENCE WET					
PERMEABILITY	Rapid	rapid	rapid		
VOIDS FREQUENCE					
VOIDS SIZE					
VOIDS TYPE					
MOTTLES FREQUENCE					
MOTTLES SIZE					
MOTTLES CONTRAST					
MOTTLES CAUSE					
MOTTLES COLOUR					
MOTTLES FORM					
CUTANS FREQUENCE	many	many	many		
CUTANS COLOUR	Dk-Br	Dk R-Br	Dk R-Br		
CUTANS TYPE	organic	clayskins	clayskins		
CUTANS LOCATION					
NODULES FREQUENCE		Few			
NODULES SIZE		medium			
NODULES HARDNESS		soft			
NODULES TYPE		insect casts			
COARSE FRAGMENTS FREQUENCE		50%	30%		
COARSE FRAGMENTS SIZE		10-20 mm	20-250mm		
COARSE FRAGMENTS SHAPE		sub L	sub L		
COARSE FRAGMENTS TYPE		shale	shale		
ROOTS FREQUENCE	5 5	2 1	2		
ROOTS SIZE	f m	f	f		
ROOTS DISTRIBUTION					
BOUNDARY CONTRAST	clear	gradual			
BOUNDARY TOPOGRAPHY	undulating	undulating			
SAMPLE NO.	T59 (A1)	T59 (B21)	T59 (C)		

REMARKS

Stony soil

APPENDIX 2 PRINCIPAL COMPONENTS ANALYSIS OF SITE VARIABLES. ASSOCIATION OF SITE VARIABLES WITH THE FIRST 10 PRINCIPAL COMPONENTS. (For variable code see Table 2.2)

EIGENVECTORS

	PRIN1	PRIN2	PRIN3	PRIN4	PRIN5	PRIN6	PRIN7	PRIN8	PRIN9	PRIN10
X_{3} RAIN	-.136229	0.125411	-.071867	0.121472	-.034249	-.075737	0.168757	-.096070	0.140048	0.017339
X_{4} ALT	-.222192	0.045464	-.123707	0.222092	-.132034	-.073757	0.050340	0.020274	0.045027	0.032946
X_{5} ASP	-.150023	0.058017	-.063912	-.044557	0.014541	-.105356	0.079163	0.041973	0.048929	0.002495
X_{6} SL	-.115527	-.041417	0.133729	-.025119	-.252580	0.165057	0.120861	0.031223	0.266561	-.199763
X_{7} SS	0.059520	0.037771	-.092286	0.135755	0.157757	0.205655	0.035563	0.061331	0.089602	-.135294
X_{9} TK	0.225213	-.076833	0.007612	0.157907	0.043705	0.415683	-.120141	0.225054	0.129508	-.148592
X_{11} TS10	0.244422	-.009763	0.006763	0.151070	0.069196	0.410009	0.106746	0.194415	0.150292	-.128369
X_{12} RIS	0.093945	0.057370	-.035750	-.107597	0.246649	-.192409	-.077756	-.061387	-.207515	0.298666
X_{18} A1	0.100143	0.171229	-.013376	-.099402	-.323939	0.099547	0.366540	-.151174	-.147516	-.152390
X_{19} A2	0.113383	0.170172	0.005790	-.115825	0.022000	0.084354	0.356498	-.136360	-.160040	-.105258
X_{20} A3	0.175020	-.086086	-.055492	-.026720	-.044380	0.135027	-.108499	-.001237	0.123811	0.165196
X_{27} PCTSTN40	0.213107	0.035518	-.151045	-.037561	0.186101	0.102592	-.134030	0.007451	-.012133	-.054285
X_{34} HCY	0.133542	0.032215	-.147365	0.032999	-.017727	0.260853	0.071297	-.020253	-.098173	0.452360
X_{36} HCC	0.098365	0.061541	-.110801	0.011630	-.005733	0.248042	0.058735	-.021790	-.085147	0.478059
X_{36} STNA1	-.054437	-.012923	0.214015	0.017251	-.238121	0.045369	0.194633	0.072009	-.125653	0.248739
X_{37} STNA	-.059651	-.003703	0.231320	-.032551	-.063552	0.058629	0.237457	0.097476	-.132967	0.269419
X_{38} STNB	-.109940	-.027730	0.122322	0.061256	-.196097	-.039055	0.106226	-.043083	0.061166	0.068156
X_{41} PERM	0.069237	0.032280	-.065307	-.094372	-.165440	0.035549	-.111220	-.033182	0.019206	-.180186
X_{43} STRUC	0.127335	0.027779	0.091979	-.147601	-.181536	0.093523	-.056631	-.068544	0.042715	-.003798
X_{44} HUEA	-.037001	0.132255	0.016962	0.031507	0.295970	-.099159	0.151720	0.292986	0.054710	0.035626
X_{45} VALA	-.010167	-.132273	0.092769	-.155777	-.005770	-.053034	-.061203	0.410777	-.165925	-.061544
X_{46} CHRA	0.014329	-.232209	0.011076	-.038669	-.255333	0.035535	-.166420	0.124965	-.157732	-.094622
X_{47} HUEB	-.126135	0.123461	-.103537	0.100326	0.276544	-.098229	0.158410	0.229304	0.020253	0.028493
X_{48} VALB	-.015455	0.097150	0.027170	-.150076	0.138446	-.110322	0.135824	0.391694	0.173812	0.113667
X_{49} CHRB	0.155306	-.045212	0.045890	-.233321	-.144503	-.062517	-.022087	0.198762	0.171916	0.051667
X_{41} WE	0.220574	0.017744	-.121772	-.115372	0.077932	0.102535	-.098384	0.015333	-.085792	-.016913
X_{40} GDP	0.204353	-.153143	-.039073	-.094164	0.035769	-.020984	-.068062	0.094693	-.003535	0.002819
X_{50} CLA	-.102643	-.341254	-.103618	-.072782	0.051536	0.041564	0.108270	-.068663	0.011314	0.031084
X_{53} SA	0.115033	0.341224	0.132973	-.030246	-.039242	-.042900	-.134654	0.040513	-.020773	0.020729
X_{54} FSA	-.040502	0.216701	-.079950	0.276171	-.165120	-.059240	-.204165	0.159399	-.136323	0.005674
X_{56} CSA	0.132629	0.137718	0.245543	-.275610	0.080135	0.003744	0.059408	-.047345	0.101680	0.023298
X_{57} CLB	-.017261	-.353659	-.043737	-.053357	0.098504	0.022180	0.086306	-.059944	-.054390	0.058149
X_{60} SAB	0.060355	0.370596	0.075375	-.029941	-.053493	-.012060	-.121606	-.003105	0.038894	-.002417
X_{61} FSB	-.026657	0.246050	-.082167	0.247334	-.191730	0.015071	-.177843	0.161254	-.138991	-.024289
X_{62} CSB	0.062794	0.161634	0.135380	-.303308	0.086497	-.044719	0.033915	-.118458	0.199541	0.026987
X_{66} AP	-.010994	0.096367	0.193018	0.021557	0.062026	0.084207	-.223977	-.174510	0.197725	0.129383
X_{69} AK	0.097700	-.139383	0.198077	0.217483	0.077456	-.075411	-.073216	-.026372	0.212494	0.147392
X_{70} ACA	0.135726	-.094698	0.200218	0.214634	0.005553	-.127699	0.013415	-.047379	0.115197	0.057678
X_{71} AMG	0.131636	-.114638	0.219872	0.211106	0.048726	-.122591	-.003623	-.032323	0.146700	0.104445
X_{72} AAL	-.211942	-.005610	0.043100	-.001306	0.112198	0.160934	-.019273	-.118695	-.112068	-.006971
X_{73} BP	0.003955	0.133266	0.113820	0.001562	0.059434	0.067701	-.099349	-.223130	0.079824	-.004666
X_{74} BK	0.067744	-.119740	0.274170	0.175921	0.133041	-.050986	-.061414	0.010143	0.018961	-.042023
X_{75} BCA	0.119450	-.045694	0.243770	0.175585	0.090868	-.027510	0.099912	0.071434	-.257549	-.003604
X_{76} BMG	0.126960	-.030396	0.228419	0.149048	0.134498	0.004090	0.077660	0.059886	-.276757	-.013252
X_{77} BAL	-.134793	-.001837	0.153364	-.002750	0.117896	0.192099	-.069439	-.169565	-.304219	-.095954
X_{83} AOC	-.105225	-.034646	-.161204	0.167102	0.130814	-.008345	0.100308	-.194773	0.189036	0.117544
X_{84} AKCL	0.193953	0.005622	-.077305	0.103067	-.063372	-.166136	0.236405	-.152241	-.065436	-.197727
X_{85} AH2O	0.252430	-.063059	0.049964	0.106894	-.044562	-.110999	0.101921	-.082024	-.026757	-.129191
X_{86} AEA	-.273943	0.010311	0.048451	-.060483	0.113401	0.173606	-.049557	-.032570	0.091575	0.054769
X_{87} BKCL	0.174306	-.032445	-.247753	0.023767	-.129659	-.135440	0.159742	-.102575	0.056508	0.047179
X_{88} BH2O	0.193930	0.018123	0.040991	0.153438	-.099710	-.069351	0.059131	-.064179	0.123830	0.046072
X_{89} BEA	-.136456	-.012393	0.237900	-.000793	0.159696	0.166627	-.069910	-.069095	-.137368	-.103650

APPENDIX 3 LOCATION OF *P. PATULA* PLOTS

(Within compartment: N = north, E = east, etc. C = central)

Plot No.	Plantation	Compt No.	Within compt	Plot No.	Plantation	Compt No.	Within compt
5	Mac Mac	D12b	E	51	Ceylon	A24	N
6	Mac Mac	D12b	C	52	Ceylon	A21	C
7	Mac Mac	D14a	SC	53	Ceylon	A29	C
8	Mac Mac	E34	C	54	Mac Mac	D8a	N
9	Mac Mac	E6	SW	55	Mac Mac	D10a	SC
10	Mac Mac	E6	NE	56	Mac Mac	D10a	NC
11	Mac Mac	C28a	NEC	57	Mac Mac	E14a	SE
12	Mac Mac	C26a	NC	58	Brooklands	E13	E
13	Mac Mac	E26a	W	59	Brooklands	E11	NW
14	Mac Mac	C26a	SW	61	Brooklands	E8	E
15	Mac Mac	E13	EC	62	Brooklands	E3	CE
16	Mac Mac	C40	EC	63	Brooklands	A50b	SW
17	Tweefontein	E31	SW	64	Brooklands	A42	N
18	Tweefontein	B19	WC	65	Brooklands	A42	CNE
19	Tweefontein	B10	NE	66	Brooklands	A42	CE
20	Tweefontein	B5	C	67	Brooklands	A42	S
21	Tweefontein	B53	E	68	Brooklands	A9	SW
22	Tweefontein	E26	SE	69	Brooklands	D40	N
23	Tweefontein	B49	W	70	Brooklands	D26	NC
24	Tweefontein	E13	S	71	Brooklands	D27	SW
25	Tweefontein	E14a	W	72	Spitskop	C36	SE
26	Tweefontein	E4	C	73	Spitskop	C28	C
27	Tweefontein	B25	CS	74	Spitskop	C20	SW
28	Tweefontein	C68	E	75	Spitskop	A6	N
29	Ceylon	G13a	NW	76	Spitskop	B39	EC
30	Ceylon	G13a	NE	77	Spitskop	B50	C
31	Ceylon	G5	NC	78	Spitskop	D50	N
32	Ceylon	G14a	C	79	Spitskop	E37	NE
33	Ceylon	G7a	C	80	Spitskop	E40	C
34	Ceylon	G7a	S	81	Spitskop	D56	C
35	Ceylon	G5	NW	82	Spitskop	D47	C
36	Ceylon	E26	NW	83	Rosehaugh	B35a	CE
37	Ceylon	E32	NC	84	Rosehaugh	B52	N
38	Ceylon	G1	NC	85	Rosehaugh	C25a	SE
39	Ceylon	E32	WC	86	Witklip	C12	SW
40	Ceylon	E47	CE	87	Witklip	B38a	NC
41	Ceylon	E47	N	88	Witklip	B34	NW
42	Ceylon	E52	C	89	Witklip	B70a	C
43	Brooklands	D7	N	90	Witklip	B39	N
44	Ceylon	F38	C	91	Witklip	B34	NC
45	Ceylon	F28	CW	92	Swartfontein	B12	C
46	Ceylon	F14	N	93	Swartfontein	B13	E
47	Ceylon	E22a	C	94	Swartfontein	B20	NEC
48	Ceylon	F41	NC	95	Swartfontein	A14	SE
49	Ceylon	E27	S	96	Swartfontein	A8a	CN
50	Ceylon	F43	NC	97	Swartfontein	A8a	SE

APPENDIX 3 (cont'd)

Plot No.	Plantation	Compt No.	Within compt	Plot No.	Plantation	Compt No.	Within compt
99	Wilgeboom	A74	C	139	Hendriksdal	C27	C
100	Wilgeboom	A74	SE	140	Hendriksdal	B26	C
101	Wilgeboom	A83	W	141	Hendriksdal	A24	NE
102	Wilgeboom	A83	EC	142	Olifantsger.	B36	CW
103	Wilgeboom	A51	C	143	Olifantsger.	C40	EC
104	Bergvliet	B52	W	144	Brooklands	E40	SE
105	Bergvliet	B47a	S	145	Brooklands	E15a	C
106	Bergvliet	B72	NC	146	Spitskop	B14a	N
107	Bergvliet	B53	W	147	Mariepskop	B26	C
108	Bergvliet	B73	C	148	Mariepskop	B21	NE
109	Bergvliet	B68	NE	149	Mariepskop	B18a	C
110	Blyde	B26	C	150	Mariepskop	B18a	NE
111	Blyde	B26	SE	151	Witklip	C15	S
112	Blyde	B25	S	152	Brooklands	E23	E
113	Blyde	B52	S	153	Brooklands	E23	SE
114	Blyde	B57	E	154	Brooklands	E26	S
115	Blyde	B44	C	155	Brooklands	E26	N
116	Blyde	B62	W	156	Elandsdrif	K9	WC
117	Blyde	B62	E	157	Elandsdrif	K12	W
118	Blyde	B69	C	158	Mac Mac	C26a	NW
119	Blyde	B74a	NE	159	Spitskop	Ala	SC
120	Blyde	B74a	S	161	Mac Mac	F6a	NC
121	Blyde	B74a	NW	162	Mac Mac	E14a	S
123	Blyde	A76	N	163	Ceylon	E26	S
124	Blyde	C8	S	164	Wilgeboom	A68	CN
125	Blyde	B87	NE	165	Wilgeboom	B21	E
126	Blyde	C6a	EC	166	Wilgeboom	B21	C
127	Blyde	C6a	N	168	Witwater	C12	S
128	Blyde	E31	C	169	Witwater	C14	SW
131	Morgenzon	A25a	N	170	Bergvliet	B73	S
132	Morgenzon	A15	CE	171	Swartfontein	B38	NE
133	Morgenzon	A16a	NE	172	Wilgeboom	C16	SE
138	Klipkraal	F70	CNE	173	Spitskop	A2	NW
				174	Spitskop	D54	NE

APPENDIX 4 FIELD SHEET FOR PLOT DATA

PROJECT 2/01/10 P.PATULA

Form A

Plot No.

1. Ptn. 2. Compt. 3.Pl. 4.Age

5. s.n. 6.Foliar sampling date

7. " " no. of trees

8. No.	9. dbh	10. Bumps	8. No.	9. dbh	10. Bumps
1			31		
2			32		
3			33		
4			34		
5			35		
6			36		
7			37		
8			38		
9			39		
10			40		
11			41		
12			42		
13			43		
14			44		
15			45		
16			46		
17			47		
18			48		
19			49		
20			50		
21			51		
22			52		
23			53		
24			54		
25			55		
26			56		
27			57		
28			58		
29			59		
30			60		

19. 30% = SELECTED TREES

20. No.	21. dbh	22. Age 3m	23. bark	24. Present ht.	25. 20 yrs ht.	26. MAI ht.	BUMPS 27. Asp.	28. Freq.	29. Prom.
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
25. Arith Mean									

11. Mean dbh
12. s/ha
13. Total b.a.
14. Mean b.a.
15. No. of trees with bumps
16. Slope %
17. Aspect
18. Rainfall:
    gauge
    period
    isohyets at gauge
    difference
    plot

30. Regression present ht.
31. " 20 yrs ht.
32. " 40 yrs ht.
33. Thinnings
34. Damage
35. Remarks

APPENDIX 5 METHOD OF ESTIMATION OF RAINFALL FOR EACH PLOT

To estimate plot rainfall, the position of each of the plots and of its nearest rain guage were plotted on the 1:250 000 rainfall isohyets maps (Government Printer, 1966). Adjustments and interpolations based on personal knowledge of the topography were made to these maps where necessary. Mean annual rainfall for each plot (IP) and its nearest rain guage (IG) were read off and recorded. For each plot, the recorded mean annual rainfall for the growth period from date of planting until 20 years of age was calculated from the records for the rain gauge nearest to that plot (RG). Plot rainfall (P) was estimated by adjusting the isohyets reading for the plot (IP) with the difference between the recorded rainfall at the nearest guage (RG) and the isohyets reading at that guage (IG):

$$P = IP + (RG - IG)$$

Records had to be traced as far back as 1931. In some cases where data within the 0 to 20 years period were missing, mean annual rainfall was calculated from all available data for the period in which the guage was operative. The problem of missing data, mainly monthly and daily records, precluded the calculation of subdivisions of rainfall such as number of rainy days or growing season rainfall.

The soundness of the method of estimating plot rainfall described above may be debatable, but no other method for extrapolation of recorded rainfall to nearby locations in such rugged terrain was available at the time. The method of interpolation between guages described by Adamson (1982) could not be used as it was only applicable in level terrain.

APPENDIX 6 SLOPE POSITION MODELS

X_9 *The Chorley model*

The model devised by Chorley (1964) classifies slope position as follows:

1. Crest
2. Free face
3. Mid slope
4. Foot slope
5. Flood plain

This model is illustrated in Fig. A.1

X_{10} *The Conacher and Dalrymple model*

The nine-unit landsurface model of Conacher and Dalrymple (1977) classifies slope position as follows:

1. Interfluve, with predominant pedogeomorphic processes being those resulting from vertical (both up and down) soil-water movements.

2. Responses to mechanical and chemical eluviation by lateral subsurface soil-water movements either predominate, or serve to distinguish this unit from other units on the catena.

3. Convex slope element where soil creep is the predominant process producing lateral movement of soil materials.

4. Slope greater than 45° characterised by the processes of fall and rock-slide.

5. Responses to transportation of a large amount of materials downslope, relative to other units, by flow, slump, slide, raindrop impact, surface wash, and man's cultivation practices.

6. Response to colluvial redeposition from upslope.

7. Response to redeposition from upvalley of alluvial materials.

8. Channel wall, distinguished by lateral corrosion by stream action.

9. Stream channel bed, with transportation of material downvalley by stream action being the predominant process.

This model is illustrated in Fig. A.2.

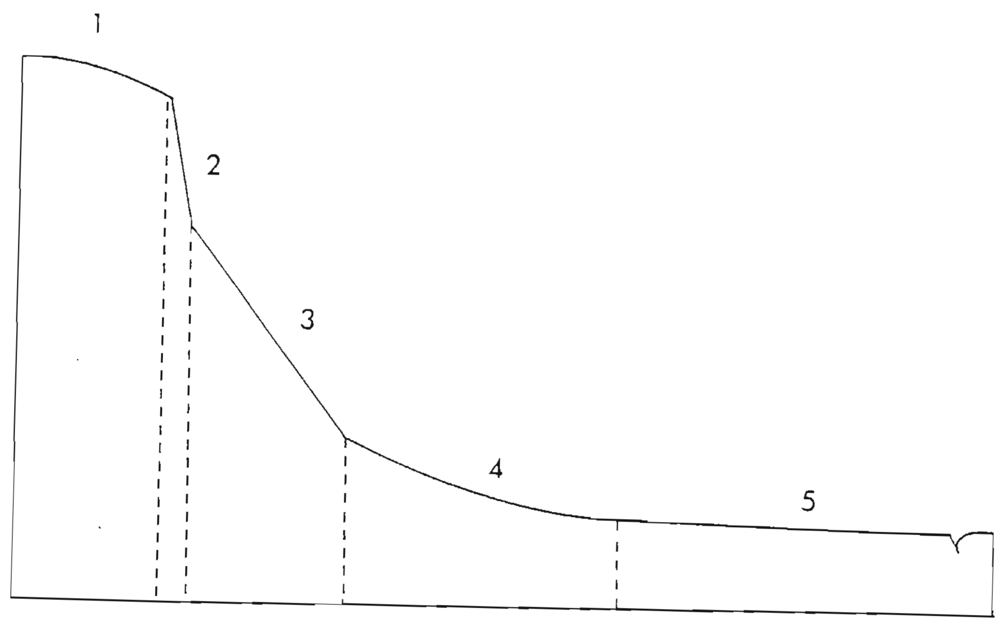


Figure A.1 Two - dimensional representation of the Chorley slope position model

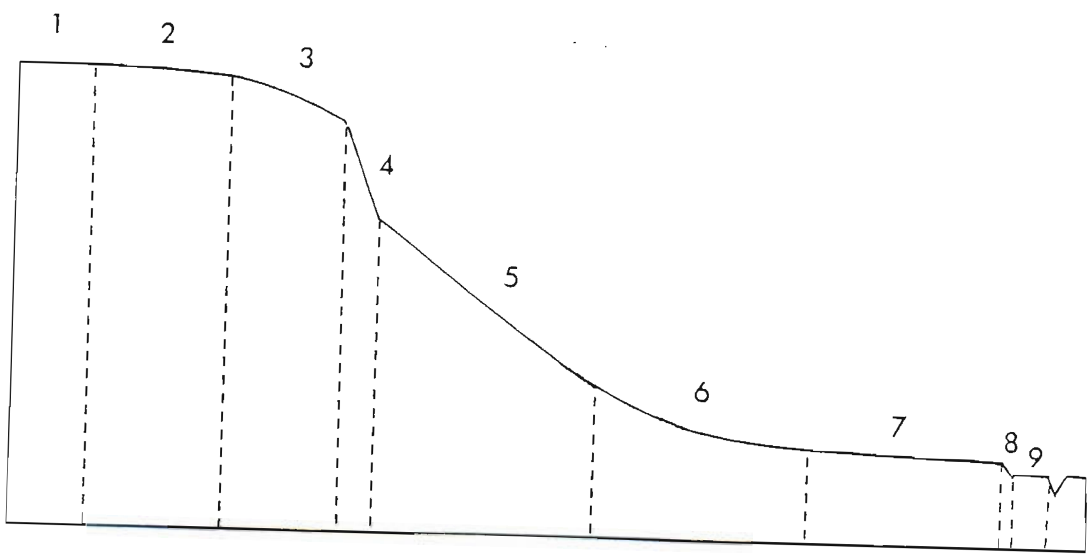


Figure A.2 Two - dimensional representation of the Conacher slope position model

X_{11} *Local model 1*

The author devised the following model to make up for the deficiencies of the preceding models when applied in the Eastern Transvaal Escarpment area. It represents a refinement of the Chorley model but with more units:

1. Narrow crest (<50 m wide)
2. Medium crest (50 - 100 m wide)
3. Wide crest (100 - 150 m wide)
4. Very wide crest (>200 m wide)
5. Upper slope
6. Middle slope
7. Lower slope
8. Narrow foot slope (<50 m wide)
9. Medium foot slope (50 - 100 m wide)
10. Wide foot slope (100 - 150 m wide)
11. Very wide foot slope (>200 m wide)
12. Flood plain

This model is illustrated in Fig A.3

The system is based on the hypothesis that soil moisture and nutrients could be expected to increase in the order 1 to 4 for ridge tops, 5 to 7 for mid slopes and 9 - 12 for foot slopes and flood plains.

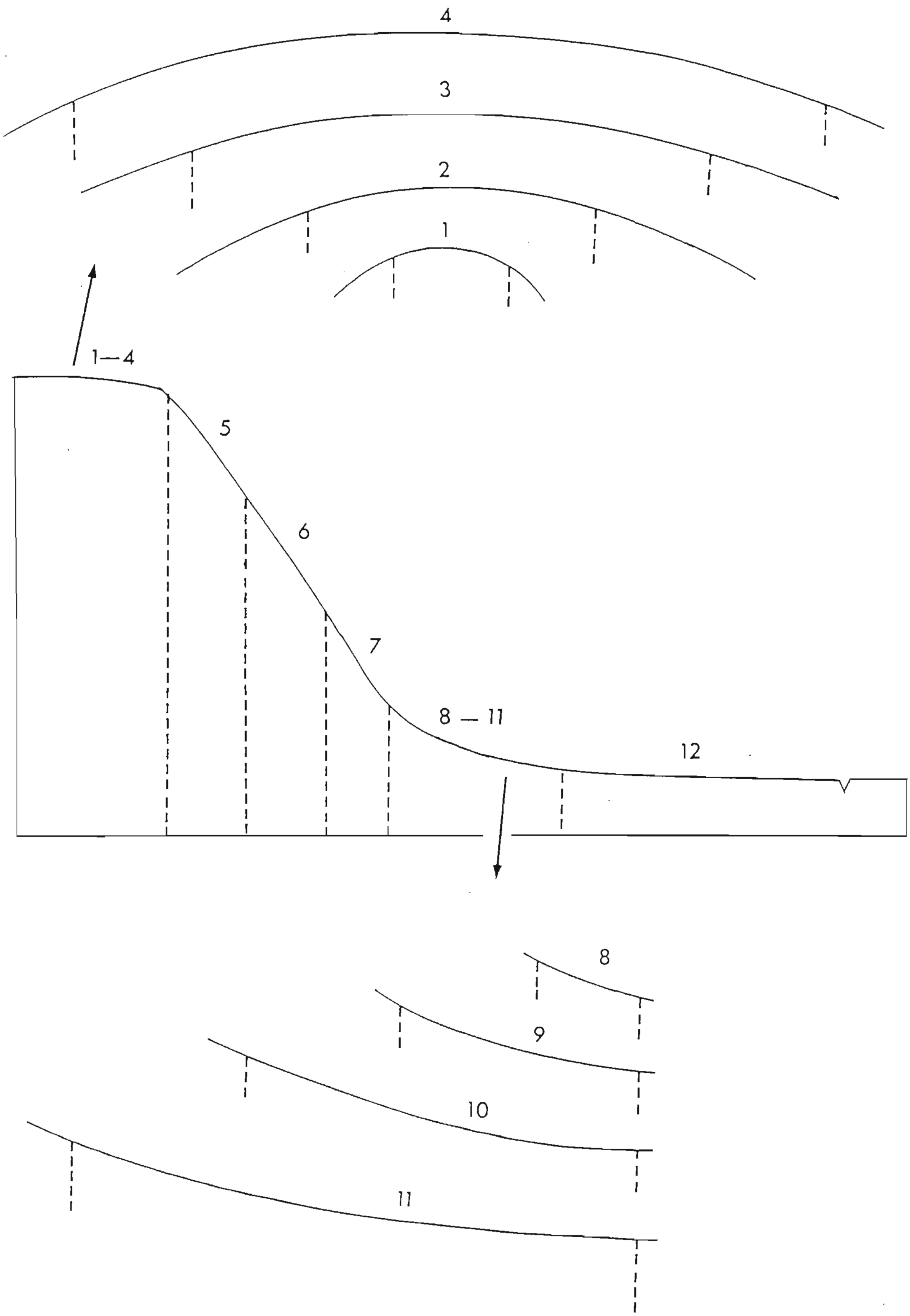
X_{12} *Local model 2*

As a preliminary study of plot locations indicated that there were insufficient plots in crest and foot slope positions to justify the subdivisions of local model no. 1, and no plots located on flood plains, a simplification led to a proposed local model no. 2:

1. Wide crest - >200 m
2. Narrow crest - <200 m
3. Upper slope
4. Middle slope
5. Lower slope
6. Foot slope

APPENDIX 6 (cont'd)

Figure A.3 Two - dimensional representation of the local slope position model



APPENDIX 7 SOIL ANALYSIS PROCEDURES

7.1 Particle size analysis

Particle size was analysed by three laboratories:

A. *D.R. de Wet Forestry Research Centre laboratory*
Removal of organic matter to ensure adequate dispersion was by means of pretreatment with hydrogen peroxide. The hydrometer method (Black, 1965, P 562) was used for the subsequent analysis and the results reported in g 100 g^{-1} of clay, silt, clay plus silt, total sand, coarse sand, medium sand and fine sand.

B. *S.A. Co-operative Citrus Exchange Ltd. laboratory*
The same methods as above were used.

C. *Natal University Soil Science Dept. laboratory*
Pretreatment for dispersion was by the ultrasonic method. A Braun Labsonic 1510 sonicator was used. A paste of 10 g soil with 15 ml calgon (20 ml in the case of samples high in clay) was sonicated for 5 minutes' duration at 400 watts. The pipette method (Black, 1965, p 552) was then used for particle size analysis.

Analysis results of 10 samples are compared for the three laboratories in Table A.1. All samples were analysed by laboratory A. It soon became apparent, however, that there were problems with soils high in manganese oxides. Normally the reaction time necessary for removal of organic matter by H_2O_2 is seldom longer than a few hours. However, as H_2O_2 also reacts with manganese oxides, severe dispersion problems arose in the case of soils derived mainly from dolomite. These soils prolonged the reaction time with H_2O_2 to as much as 72 hours in some cases, in spite of continual replenishment of H_2O_2. Even then satisfactory dispersion was evidently not obtained, as textural assessment by feel indicated that silt plus clay values were unusually low, or in some cases acceptable but with silt too high relative to clay, e.g. T 111 (Table A.1).

No problems were experienced with soils derived from granite, Black Reef or the Selati Formations, as manganese levels in these soils are relatively low. Dolomite soils were the most problematic, followed by those of the Oaktree Formation (which is associated with dolomite) and diabase intrusions into the

APPENDIX 7 (cont'd)

Table A.1 Comparison of particle size analyses by different laboratories.

Pretreatment for dispersion:

A = H_2O_2 /calgon (D.R. de Wet F.R.C.)
B = H_2O_2 /calgon (Citrus Exchange)
C = Ultrasonic / calgon (Natal University)

Plot no.	Horizon	Soil origin	Method	Clay	Silt	Clay + silt
					g 100 g^{-1}	
T100	A1	Dolomite	A	23	20	43
			B	24	35	59
			C	43	28	71
T100	B21	Dolomite	A	36	25	61
			B	44	35	79
			C	51	23	74
P11	A1	Dolomite	A	32	30	62
			B	22	27	49
			C	56	15	71
E87	B21	Dolomite	A	23	24	47
			B	16	27	43
			C	32	26	58
E63	A1	Dolomite	A	19	21	40
			C	52	17	69
E63	B21	Dolomite	A	31	25	56
			C	54	17	71
E140	A1	Dolomite	A	3	20	23
			C	30	41	71
T111	A1	Diabase	A	7	63	67
			C	49	20	69
P29 (low Mn)	A1	Timeball	A	42	26	68
			C	42	24	66
P173 (low Mn)	A1	Oaktree	A	32	18	50
			C	30	16	46

APPENDIX 7 (cont'd)

Timeball shales through the underlying dolomite. Soils derived from Timeball shales gave problems if diabase colluvium was present or in close proximity.

It was also noticable that there were more problems with A than with B horizons, e.g. E 63 (Table A.1). This is thought to be due to the higher organic matter present in surface horizons prolonging the reaction time with H_2O_2.

For confirmation of the problem, several samples were re-analysed by laboratory B. The results shown in Table A.1 confirm the problem and that use of H_2O_2 is inappropriate in the case of soils derived from dolomite and related substrates with high manganese levels.

Satisfactory results were eventually obtained using ultrasonic dispersion (laboratory C). All dolomite-derived soils and others with suspect particle size analyses were re-analysed by this method. Several samples from other soils low in manganese were included as a check and results were found to agree closely with those obtained at the D.R. de Wet laboratory. (Table A.1). The writer could find no references to this problem in the literature.

7.2 Available phosphorus

Available P was extracted from the soil using the Bray 2 solution and determined colorimetrically with a Technicon Auto Analyzer. The method described in FSSA (1980) was slightly modified: 50 ml of Bray 2 extracting solution was added to 6,7 g soil and shaken for 40 seconds at 80 cycles in a reciprocating shaker. Phosphorus was determined on the filtrate using the following reagents in the auto analyzer: (1) molybdate reagent (ammonium molybdate in dilute H_2SO_4), (2) reducing agent (sodium sulphite, sodium metabisulphite and 1-amino-2-naphthol-4-sulphonic acid), (3) standard solutions (potassium dihydrogen phosphate in distilled water).

7.3 Exhangeable bases

Exhangeable K, Ca and Mg were extracted using the method described in FSSA (1980). 50 ml of ammonium acetate extracting solution were added to 5 g soil and shaken for 15 minutes at 180 rpm. K, Ca and Mg were then determined by

APPENDIX 7 (cont'd)

atomic absorption.

7.4 **Exchangeable aluminium**

50 ml of 0,2 N ammonium chloride were added to 5 g soil and shaken for 10 minutes. Exchangeable aluminium was determined on the filtrate using the following reagents in the auto analyzer: 7,0 M ammonium acetate, 5 M HCl, aluminon solution (aluminon, NaOH, acetic acid and Brij solution), thioglycolic acid and standard solutions.

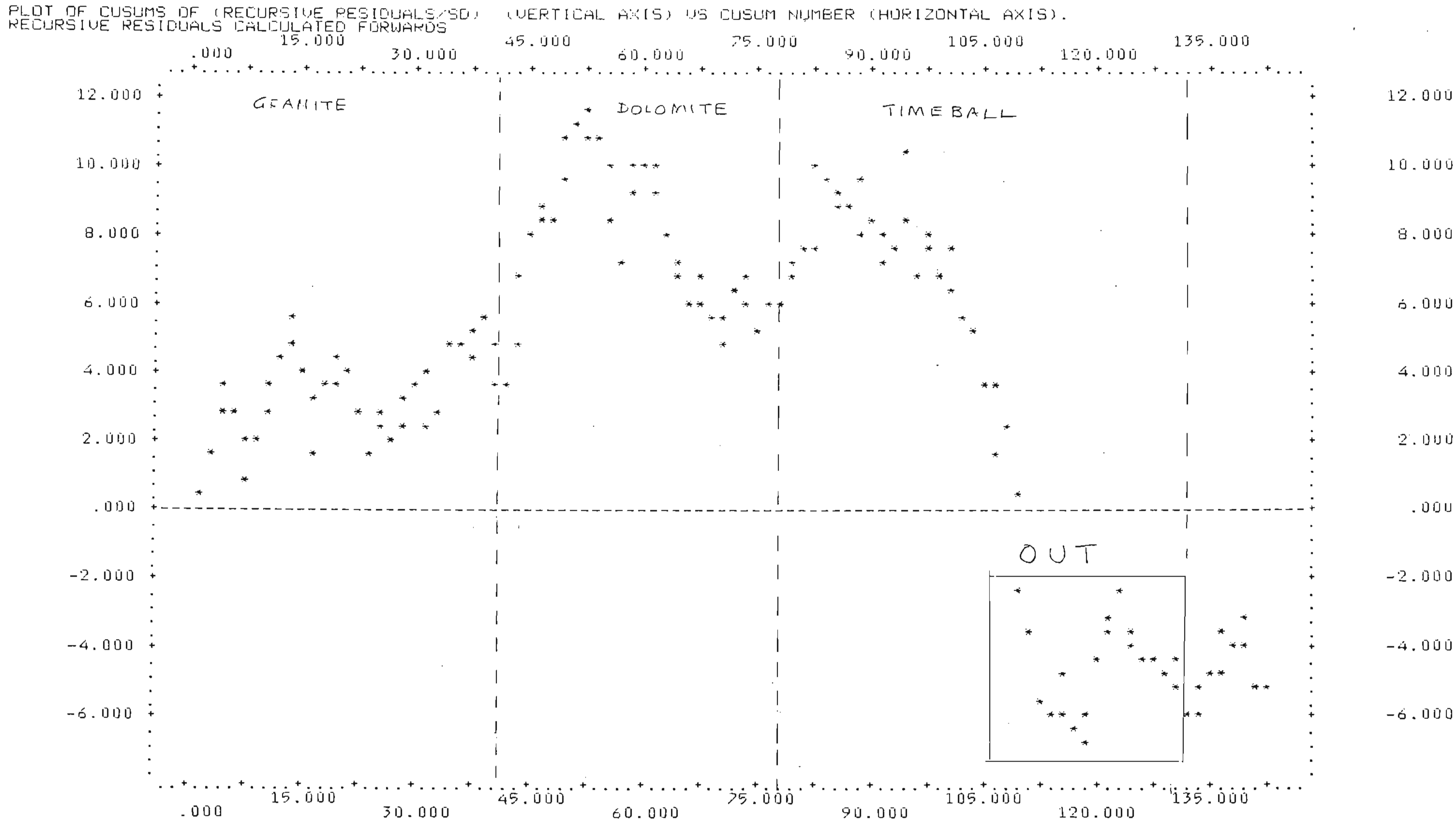
7.5 **Organic carbon**

This was determined by the Walkley-Black wet oxidation procedure (Black, 1965, p 1372) but modified by Natal University Soil Science Dept. as follows: After treatment with H_2SO_4 and addition of H_3PO_4, 10 drops of ferroin instead of 3-4 drops are added, together with 0,2 g NaF. Titration is done with 0,5 N ferrous ammonium sulphate instead of ferrous sulphate.

7.6 **Exchange acidity**

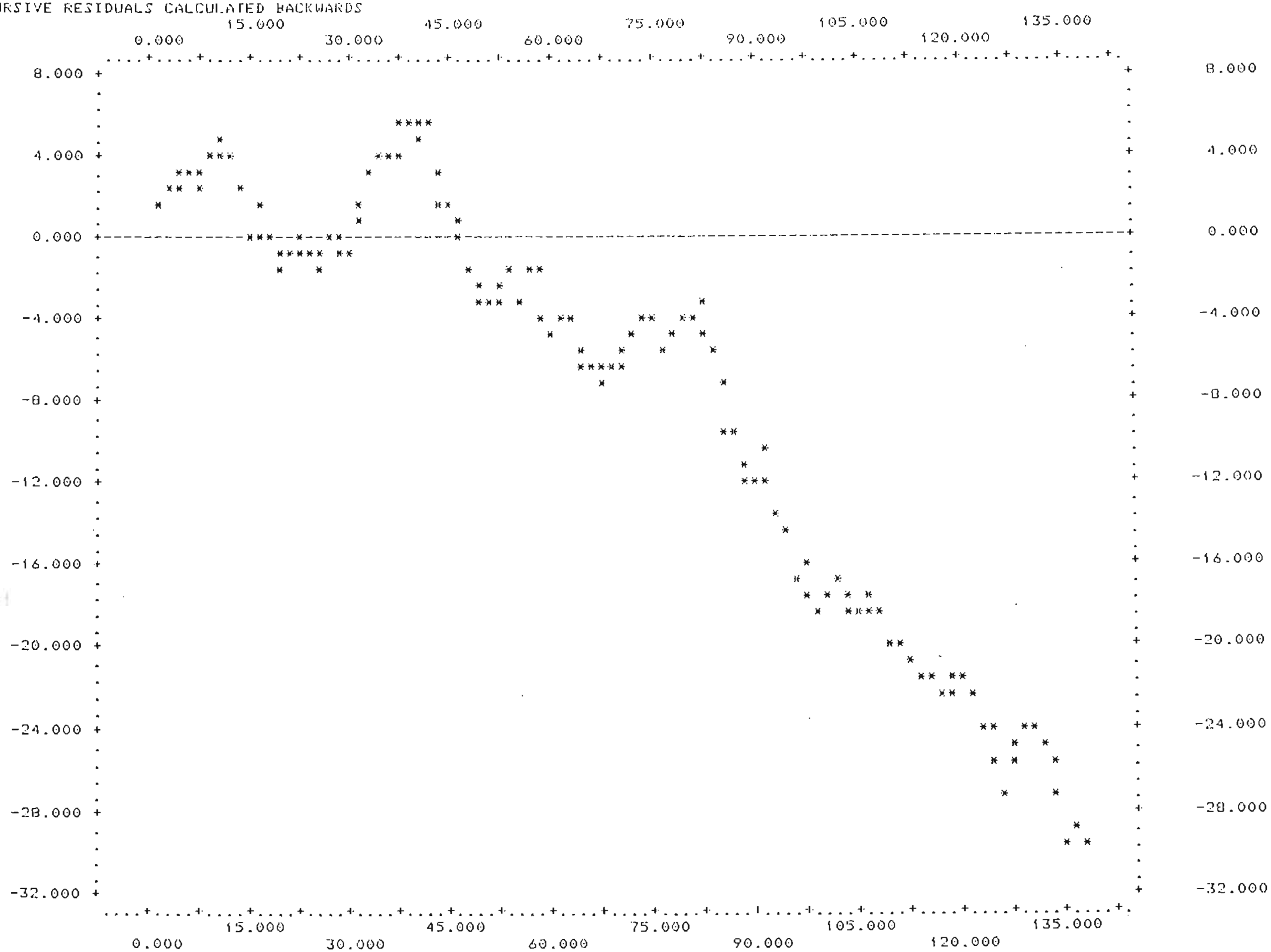
After testing the KCl samples for pH, a further 25 ml of KCl was added and the samples centrifuged at 1 000 rpm for 5 minutes. A few drops of phenolphthalein indicator were added to 25 ml of the supernatant which was titrated with standard 0,01 N NaOH. This is a procedure modified from that described in FSSA (1980).

APPENDIX 8.1 CUSUM PLOT FOR MODEL 3.4 WITH SITES ORDERED ON GEOLOGY.



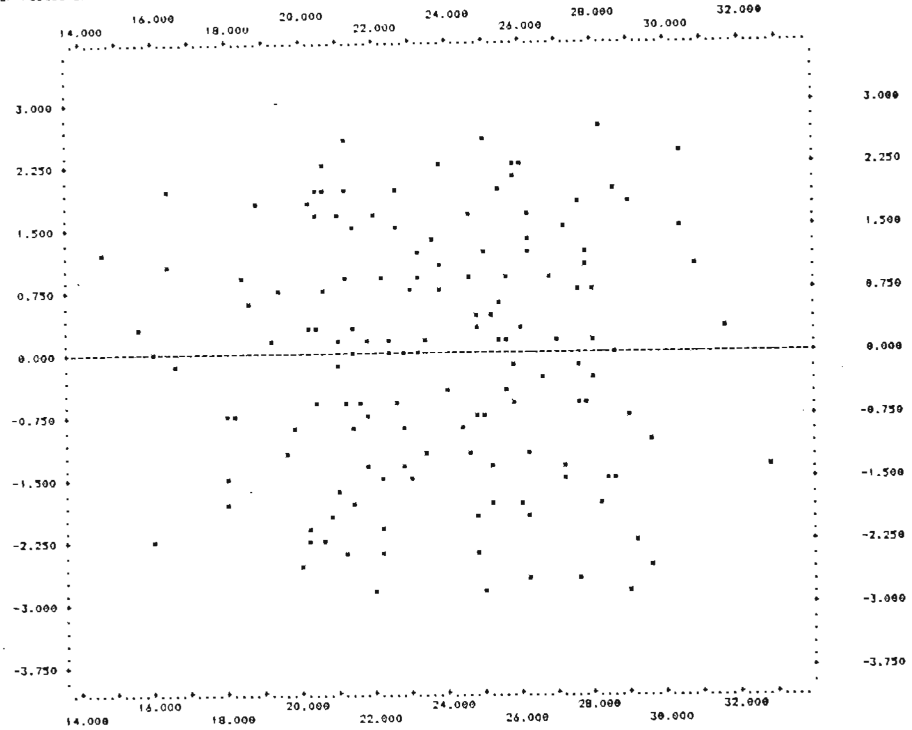
APPENDIX 8.2 CUSUM PLOT FOR MODEL 2.5

T OF CUSUMS OF (RECURSIVE RESIDUALS/SD) (VERTICAL AXIS) VS CUSUM NUMBER (HORIZONTAL AXIS).
URSIVE RESIDUALS CALCULATED BACKWARDS

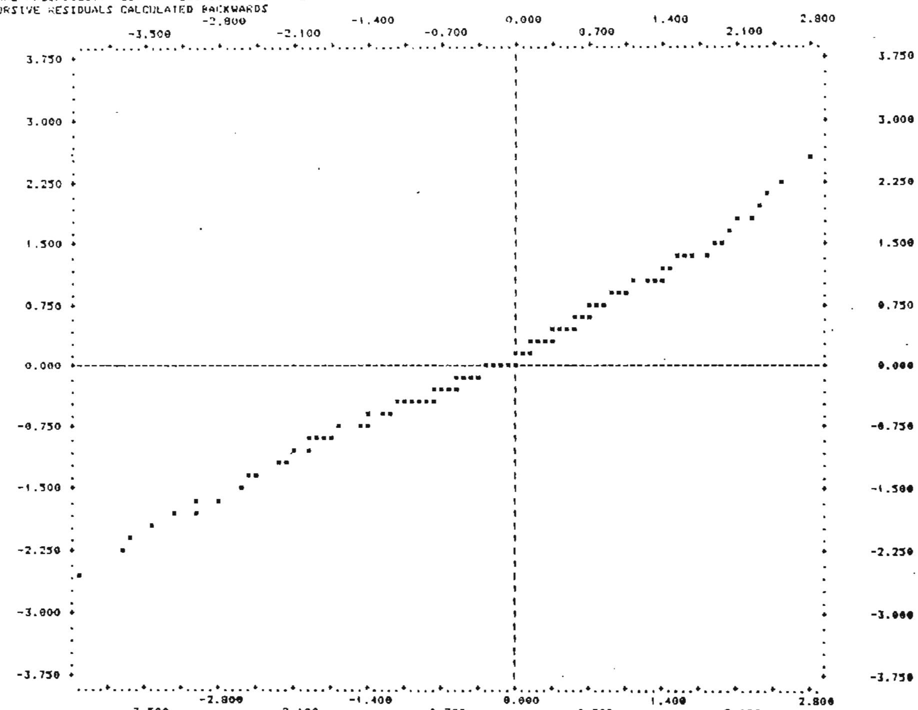


APPENDIX 8.3 RESIDUAL PLOTS FOR MODEL 2.5

PLOT OF RESIDUALS (VERTICAL AXIS) VS PREDICTED (HORIZONTAL AXIS).



NORMAL PROBABILITY PLOT OF RECURSIVE RESIDUALS: (STANDARD NORMAL ORDINATE (VERTICAL AXIS) VS RECURSIVE RESIDUALS (HORIZONTAL AXIS).)
RECURSIVE RESIDUALS CALCULATED BACKWARDS



NORMAL PROBABILITY PLOT CORRELATION COEFFICIENT IS 0.995372

APPENDIX 9 CORRELATION COEFFICIENTS SIGNIFICANT AT 0,001% LEVEL BETWEEN FOLIAR NUTRIENTS AND SITE AND STAND FACTORS (for variable code see table 2.2)

Element	Correlation coefficients
N	X_{41}(-0,3) X_{43}(-0,3) X_{44}(-0,3) X_{45}(0,4) X_{48}(0,4) X_{65}(-0,4) X_{66}(-0,3) X_{84}(0,4) X_{86}(-0,3) X_{87}(0,3)
P	X_{13}(-0,3) X_{15}(-0,3) X_{16}(-0,3) X_{17}(-0,3)
K	X_{52}(-0,4) X_{53}(-0,4) X_{56}(0,3) X_{57}(0,3) X_{59}(-0,3) X_{64}(0,3) X_{66}(0,4)
Ca	X_{3}(-0,5) X_{4}(-0,4) X_{11}(0,4) X_{20}(0,4) X_{21}(0,4) X_{22}(0,4) X_{27}(0,3) X_{41}(0,5) X_{45}(-0,4) X_{47}(0,3) X_{48}(-0,4) X_{65}(0,4) X_{66}(0,4) X_{67}(0,4) X_{84}(-0,4) X $_{85}$(0,3) X_{86}(0,5) X_{87}(-0,4) X_{89}(0,4) X_{104}(0,4) X_{106}(0,5) X_{107}(0,5)
Mg	X_{13}(-0,3) X_{16}(-0,4) X_{17}(-0,03) X_{22}(0,3) X_{27}(0,3) X_{52}(-0,3) X_{53}(-0,4) X_{56}(0,3) X_{57}(0,3) X_{58}(-0,3) X_{60}(-0,4)
Na	X_{4}(0,3) X_{6}(0,3) X_{14}(-0,3) X_{21}(0,3) X_{41}(-0,3) X_{51}(0,2) X_{67}(-0,3) X_{104}(-0,3) X_{106}(-0,3) X_{107}(-0,3)
S	None
Cu	X_{52}(-0,3) X_{57}(0,3) X_{64}(0,3)
Fe	X_{22}(0,3) X_{52}(-0,4) X_{53}(-0,3) X_{56}(0,3) X_{60}-0,3) X_{100}(-0,5)
Mn	X_{41}(0,3 X_{49}(-0,3) X_{52}(0,3) X_{56}(-0,3) X_{57}(-0,4) X_{59}(0,3) X_{64}(-0,4)
Zn	X_{4}(0,3) X_{64}(-0,3) X_{104}(0,3)
B	X_{20}(-0,3) X_{27}(-0,3) X_{41}(-0,3) X_{87}(0,3) X_{104}(-0,5) X_{106}(-0,4)
Al	X_{5}(-0,3)

APPENDIX 10 *P. PATULA* FOLIAR NUTRIENT CONCENTRATIONS (8-10 TREES BULK SAMPLES) FOR SITES >26 m *SITE INDEX* (MACRO ELEMENTS: % D.M., MICRO ELEMENTS mg kg^{-1}).

OBS NO.	SITE NO.	S.I. (m)	N	P	K	Ca	Mg	Na	S	Cu	Fe	Mn	Zn	B	Al
1	124	32,9	1,90	0,20	1,07	0,61	0,21	0,02	0,19	4	106	1289	27	25	388
2	18	31,9	1,92	0,16	0,84	0,56	0,21	0,01	0,08	3	94	1001	29	15	1188
3	158	31,9	2,04	0,17	0,90	0,32	0,19	0,03	0,13	5	121	847	38	15	438
4	126	31,4	1,92	0,17	1,15	0,60	0,25	0,02	0,16	4	117	1095	30	18	375
5	152	31,4	2,20	0,16	1,08	0,36	0,11	0,02	0,15	5	174	1009	26	23	450
6	87	30,9	2,02	0,18	1,32	0,30	0,16	0,01	0,13	5	111	385	23	20	438
7	53	30,8	2,19	0,19	0,77	0,30	0,16	0,05	0,12	7	51	1269	27	23	750
8	12	30,5	2,26	0,15	0,83	0,30	0,12	0,03	0,13	6	109	1011	28	13	725
9	51	30,4	2,04	0,15	0,64	0,16	0,09	0,03	0,22	4	70	1883	18	23	575
10	86	29,5	2,04	0,18	1,15	0,31	0,19	0,02	0,15	8	141	633	22	23	430
11	97	29,1	2,10	0,18	0,93	0,42	0,20	0,02	0,14	5	100	289	24	25	388
12	14	28,9	2,12	0,15	0,79	0,31	0,13	0,02	0,08	5	80	2428	29	15	725
13	27	28,6	2,28	0,18	0,99	0,37	0,20	0,02	0,08	4	76	1266	38	13	850
14	93	28,6	2,14	0,20	1,27	0,38	0,16	0,03	0,07	7	103	342	26	25	350
15	95	28,6	2,10	0,17	1,01	0,34	0,13	0,02	0,05	5	118	529	21	25	375
16	82	28,5	2,14	0,18	1,22	0,37	0,16	0,01	0,14	5	120	501	31	23	438
17	23	28,4	2,04	0,16	1,01	0,39	0,15	0,01	0,40	3	74	1220	24	13	875
18	83	28,3	2,00	0,17	1,17	0,43	0,22	0,01	0,26	6	291	336	31	23	388
19	91	28,2	2,04	0,16	0,85	0,39	0,18	0,03	0,08	6	151	613	23	23	450
20	153	28,2	2,18	0,18	1,02	0,35	0,14	0,03	0,25	7	174	945	9	30	438
21	80	28.1	2.12	0.18	1,08	0,19	0,16	0,02	0,10	7	199	2187	33	20	400
22	103	28,1	1,92	0,17	0,81	0,21	0,19	0,05	0,18	11	119	1088	16	30	363
23	155	27,9	2,26	0,20	0,78	0,28	0,14	0,09	0,25	5	159	2411	21	23	438
24	11	27,8	2,30	0,13	0,66	0,25	0,13	0,01	0,15	4	112	2153	24	15	813
25	20	27,8	2,14	0,18	0,81	0,27	0,14	0,01	0,23	3	67	1586	19	13	800
26	8	27,8	2,18	0,15	0,86	0,23	0,11	0,01	0,08	4	86	1266	29	13	663
27	139	27,6	1,98	0,17	0,76	0,36	0,18	0,01	0,17	3	145	2334	21	28	313
28	108	27,6	2,10	0,16	1,12	0,32	0,17	0,01	0,20	5	114	803	25	15	425
29	81	27,5	2,02	0,17	1,03	0,14	0,14	0,02	0,15	6	165	679	23	25	425
30	17	27,5	1,96	0,16	0,86	0,44	0,17	0,01	0,25	4	77	1445	43	15	900
31	96	27,4	2,00	0,17	0,93	0,33	0,16	0,03	0,11	4	110	343	17	23	413
32	19	27,3	2,08	0,14	0,71	0,25	0,13	0,02	0,16	3	108	2210	23	15	600
33	88	27,3	2,20	0,19	1,04	0,33	0,22	0,02	0,10	7	110	599	20	28	475
34	78	27,2	2,30	0,20	0,88	0,27	0,13	0,02	0,05	4	37	722	27	20	338
35	144	27,2	2,08	0,17	0,90	0,27	0,15	0,03	0,18	3	129	2341	25	23	325
36	24	27,1	2,10	0,17	0,90	0,44	0,17	0,02	0,08	4	75	1140	35	13	813
37	104	27,1	2,14	0,18	0,93	0,30	0,18	0,05	0,10	5	130	850	28	18	400
38	84	27,0	1,92	0,19	1,12	0,42	0,18	0,01	0,17	6	162	725	25	25	438
39	28	26,9	2,24	0,17	0,46	0,37	0,16	0,03	0,13	7	73	1149	41	18	863
40	90	26,9	1,96	0,18	0,99	0,23	0,26	0,07	0,06	14	154	505	19	23	425
41	128	26,4	2,16	0,15	0,94	0,31	0,16	0,01	0,15	7	143	1648	29	18	363
42	109	26,4	2,00	0,16	0,95	0,34	0,19	0,01	0,12	4	176	1079	23	15	425
43	140	26,4	1,96	0,18	0,83	0,38	0,18	0,01	0,12	4	189	2104	28	28	313
44	143	26,3	2,06	0,15	0,88	0,43	0,22	0,01	0,31	3	139	2330	31	15	300
45	92	26,2	2,00	0,19	1,20	0,45	0,20	0,03	0,07	12	115	276	24	38	438
46	107	26,2	2,24	0,19	1,10	0,30	0,17	0,01	0,18	4	150	892	21	20	350
47	151	26,1	2,22	0,17	1,03	0,19	0,17	0,03	0,22	4	128	727	17	20	388
48	7	26,1	2,24	0,15	0,68	0,20	0,14	0,02	0,13	3	101	2252	22	13	463

APPENDIX 11 *P. PATULA* PROVISIONAL DRIS NORMS FOR FOLIAR NUTRIENT EXPRESSIONS DERIVED FROM TREES >26 M SITE INDEX.

EXPRESSION	NORM	S.D.	C.V.%	EXPRESSION	NORM	S.D.	C.V.%	EXPRESSION	NORM	S.D.	C.V.%
N/P	12,37	1,48	11,98	K/S	7,84	4,32	55,12	Na/Fe	0,000235	0,00	79,55
N/K	2,32	0,58	24,97	K/Cu	0,1998	0,06	31,64	Na/Mn	0,0000288	0,00	98,85
N/Ca	6,91	2,41	34,82	K/Fe	0,0086	0,00	39,70	Na/Zn	0,000907	0,00	86,53
N/Mg	13,14	3,33	25,37	K/Mn	0,00124	0,00	81,37	Na/B	0,00142	0,00	63,69
N/Na	126,06	64,30	51,01	K/Zn	0,037	0,01	27,66	Na/Al	0,0000582	0,00	77,96
N/S	17,36	8,84	50,92	K/B	0,0472	0,01	27,87	S/Cu	0,0348	0,02	71,53
N/Cu	0,45	0,15	33,13	K/Al	0,00204	0,00	37,55	S/Fe	0,00145	0,00	65,36
N/Fe	0,0202	0,01	46,61	Ca/Mg	2,01	0,49	24,44	S/Mn	0,000169	0,00	76,93
N/Mn	0,00237	0,00	66,90	Ca/Na	20,97	13,33	63,596	S/Zn	0,00575	0,00	54,34
N/Zn	0,0843	0,02	22,37	Ca/S	2,76	1,60	57,93	S/B	0,00791	0,01	63,74
N/B	0,11	0,03	29,86	Ca/Cu	0,0732	0,04	49,18	S/Al	0,000326	0,00	56,74
N/Al	0,00455	0,00	29,16	Ca/Fe	0,00311	0,00	48,86	Cu/Fe	0,0480	0,03	52,63
P/K	0,19	0,04	20,52	Ca/Mn	0,000397	0,00	82,6	Cu/Mn	0,00729	0,01	105,83
P/Ca	0,56	0,18	33,07	Ca/Zn	0,01306	0,00	28,15	Cu/Zn	0,22	0,13	59,46
P/Mg	1,06	0,22	20,50	Ca/B	0,0176	0,01	41,22	Cu/B	0,26	0,09	33,78
P/Na	10,20	5,18	50,78	Ca/Al	0,000708	0,00	44,70	Cu/Al	0,01117	0,01	54,76
P/S	1,43	0,77	53,86	Mg/Na	10,18	5,81	57,08	Fe/Mn	0,16	0,14	91,77
P/Cu	0,0366	0,01	31,38	Mg/S	1,39	0,78	55,6	Fe/Zn	4,92	1,93	39,33
P/Fe	0,00159	0,00	48,60	Mg/Cu	0,0358	0,01	38,58	Fe/B	6,18	2,13	34,52
P/Mn	0,00022	0,00	72,84	Mg/Fe	0,00154	0,00	39,08	Fe/Al	0,28	0,15	53,41
P/Zn	0,0069	0,00	24,73	Mg/Mn	0,000215	0,00	78,86	Mn/Zn	47,00	29,15	62,02
P/B	0,00888	0,00	24,11	Mg/Zn	0,00675	0,00	31,15	Mn/B	65,32	43,96	67,29
P/Al	0,000439	0,00	33,15	Mg/B	0,00875	0,00	31,95	Mn/Al	2,55	1,86	73,16
K/Ca	3,05	1,08	35,35	Mg/Al	0,000372	0,00	40,51	Zn/B	1,41	0,61	43,07
K/Mg	5,79	1,36	23,52	Na/S	0,1997	0,19	95,61	Zn/Al	0,0557	0,02	33,14
K/Na	57,85	33,07	57,17	Na/Cu	0,00452	0,00	63,03	B/Al	0,0465	0,02	46,07

APPENDIX 12 PLOT OF RESIDUALS VS. PREDICTED VALUES FOR *LITTER THICKNESS*

PLOT OF RESIDUALS (VERTICAL AXIS) VS PREDICTED (HORIZONTAL AXIS).