1

INTRODUCTION

1.1 BACKGROUND

Food security and the development of sustainable systems for the use of land and water resources will remain key concerns for the 21st century in many regions of the world (Gill, 2001). An enormous threat to food security for the human race is the decrease in yields from agricultural lands that are physically, chemically and biologically degraded through the use of unsustainable farming practices. It is, however, increasingly realized that the development of rural agriculture can solve simultaneously several of the world's most acute problems e.g. poverty, food insecurity and land degradation.

One of the focus areas of the South African Government is to increase the positive impact agriculture can have in our rural areas (Didiza, 2000). However, soil acidity is a major factor limiting agricultural production in South Africa. Some 3 million hectares of the communal agricultural areas of South Africa (former homelands), have rainfall and rainfall patterns that are relatively favourable for crops, livestock and pasture production according to South African conditions. The major portion of medium to high agricultural potential land in South Africa is found in the former Ciskei, KwaZulu-Natal, Transkei and eastern parts of the Mpumalanga Province. These areas include approximately 1.2 million high potential land with a mean annual rainfall that exceeds 700 mm (Van der Merwe & Walters, unpublished). However, agricultural production potential in these areas is seriously jeopardized due to excessive soil acidity.

1.2 JUSTIFICATION

In 1997 the Mpumalanga Department of Agriculture, Conservation and Environment (MDACE) hosted a Workshop on Soil Acidity to promote sustainable agricultural land use. The rationale behind this Workshop was that soil acidity impacts severely on agricultural productivity in many areas of Mpumalanga. This resulted in unsustainable crop production, especially in the higher rainfall areas that includes many of the resource-poor farmers in the province. This Workshop was to form part of the launching of the National Landcare Programme (NLP) of the Department of Agriculture (DoA). Various thematic issues on soil acidity were introduced by keynote speakers. The aimed outcome was the development of various interventions with champions to take these forward.

The NLP themes were grouped into two main areas, namely Focused Investment (WaterCare, VeldCare, SoilCare, Eco-Agriculture Expanded LandCare and Junior Care) and Small Community Grants. The SoilCare theme targeted rural communities in Mpumalanga, Eastern Cape and KwaZulu-Natal with strategic objectives:

(i) of reducing depletion of soil fertility and reducing soil acidity,
(ii) to build innovative structures to combat soil erosion and
(iii) to introduce sustainable management of agricultural production systems (*i.e.* through diversification, or management of inputs, e.g. resulting in reduced pollution and the adoption of minimum tillage).

Up to 1997 soil acidity has mostly been neglected in the communal areas of Mpumalanga. However, in conjunction with the 1997 Workshop, the Eastern Transvaal Small Farmers Forum (ETSFF), situated in the Mlondozi district (former Kangwane), approached the MDACE for assistance (Xaba, 2002). It soon became clear that resource-poor farmers in this district were adversely affected by soil acidity, as 90% of all soils that were analyzed had pH (KCl) values below 4.2. Furthermore, the land tenureship system does not guarantee continuous ownership of land, rendering a problem in the Mlondozi district. Land users were not prepared to make a long-term investment by liming their soils. The MDACE, together with the ETSFF applied for financial assistance from the DoA for implementing a lime subsidy of 5 tonnes ha^{-1} cultivated land for the Mlondozi land users. An amount of R 2.5 million was granted in 1997 to launch the Mlondozi Landcare project that would benefit 1500 farmers cultivating 4000 ha.

1.3 SOUTH AFRICAN LANDCARE PROGRAMME

1.3.1 Goal of the national Landcare programme

The goal of the NLP in South Africa was to optimize productivity and sustainability of natural resources resulting in greater productivity, food security, job creation and a better quality of life for all (DoA, 2005).

1.3.2 National Landcare principles

Philosophically, and as a policy area, Landcare in South Africa is concerned with the application of six indivisible Landcare principles (DoA, 2005):

(i) *Integrated Sustainable Natural Resource Management* embedded within a holistic policy and strategic framework where the primary causes of natural resource decline are recognized and addressed.

(ii) *Fostering group or community* based and led natural resource management within a participatory framework that includes all land users, both rural and urban, so that they take ownership of the process and the outcomes.

(iii) The development of *sustainable livelihoods* for individuals, groups and communities utilizing empowerment strategies.

(iv) Government, community and individual *capacity building* through targeted training, education, and support mechanisms.

(v) The development of active and true *partnerships* between government, Landcare groups and communities, non-government organizations, and industry.

(vi) The blending together of appropriate upper level *policy processes* with *bottom up feedback mechanisms*. Feedback mechanism should utilize effective Landcare Programme beneficiaries and supporting participants.

1.3.3 Purpose of the South African Landcare programme

The following purposes contribute to a lesser or greater extent to the achievement of the overall Landcare goal (DoA, 2005):

(i) *Conservation of natural resources (community-based approach):*

National support system recognizes local support structures or institutions.

Participatory legislation, policies, norms and standards implemented to support the wise use of natural resources.

Community-based natural resource management.

(ii) *Sustainable improved productivity:*

Adoption of sound land management practices by all land users, resulting in increased productivity through the improvement of the natural resource base.

(iii) *Food security:*

Protect natural resources.
Improve productivity of farming systems.
Access to food, land and information.
Safety and security of food.
Quality of food.
Off-farm income.

(iv) *Empowerment (social, economic, employment and equity):*

The purpose of empowerment in Landcare is to enhance economic capacity of land users to achieve self-sufficiency by utilizing natural resources in order to:

Improve the quality of life.
Create entrepreneurial skills.
Diversify income sources.
Improve infrastructure.
Invest in human resources.

1.4 THE MLONDOZI LANDCARE PROJECT

In support of the NLP, the Agricultural Research Council-Institute for Soil, Climate and Water (ARC-ISCW) initiated the Mlondozi Landcare project under the SoilCare theme of the NLP, in collaboration with Southern Highveld Region Extension, Mlondozi farmers and farmer associations. The goal of the Mlondozi Landcare project was to demonstrate and assess sound land management practices, by involving local communities, who will contribute to sustainable and profitable agricultural production in the Mlondozi district.

The ARC-ISCW was contracted to monitor and evaluate the project that was initiated in September 1997. Reference soil samples were collected to determine the background soil acidity and fertility status of the district. Trials were set up at two sites in 1997 to demonstrate the benefits of liming to the farming community. Through rural appraisal, needs and diagnostic surveys it was found that the majority of farmers were subsistence, experiencing food insecurity with a low standard of living. Historically the area was primarily used for seasonal grazing because of the climatic unsuitability for crop farming. At the start of the project the challenge was to improve the maize yield in the district from a mere 0.5 tonnes ha^{-1} to an estimated district potential of approximately 4.5 tonnes ha^{-1}. At the time farmers were using unsustainable farming practices such as: incorrect soil fertility and weed management practices, late planting dates, mono-cropping, over-grazing and ploughing the land at very high cost. Ploughing furthermore led to in-field soil erosion, soil biological degradation and declining soil fertility. These inappropriate land management practices also caused the soil to become more compacted, the organic matter content to be reduced and water runoff and soil erosion to increase (Steiner, 1998). These practices also led to the effects that drought spells impacted more severely on yields and the soils became less fertile and less responsive to fertilizer. Other disadvantages of conventional production are the high requirement of labour (weeding), time and energy (fuel cost) (Steiner, 1998).). The effects of these factors in reducing yields and income are particularly apparent in regions like Mlondozi with a short growing season. Historically the area was primarily used for seasonal grazing because of the climatic unsuitability for crop farming.

Another challenge existed in that soil acidification is a natural process that is exacerbated by modern agricultural practices. The rate at which a production system acidifies is a function of the intrinsic soil properties (e.g. base saturation, CEC, buffering capacity), climate, and farming practice. It is therefore important that the rate of acid production in soils by these various inputs and outputs on different land uses be known in order to facilitate corrective actions by the producer (Sumner & Noble, 2003). Furthermore, knowledge on intrinsic mechanisms governing soil buffering capacity of major soil groups in the district could serve as a valuable tool in understanding why soils respond differently to addition of dolomite. Knowledge on a soil’s buffering capacity is also needed to understand the rates of natural soil weathering, rates of soil acidification from acid-forming nitrogen fertilizers, acid rain, and acid mine waste (Bloom, 2000). From a strategic perspective, quantification of acid production rates under various agronomic production systems can assist producers, extension officers, and policy makers in making decisions in preventing acidification and the long-term impact of a production system.

A community-driven development approach was followed in the Mlondozi Landcare project with the core principles being the training and empowerment of land users and community members in the benefits of liming and fertilization practices to improve soil productivity and to obtain stable and profitable yields. The implementation and impact of the technologies on the farming community (biophysical, economic and social indicators) were to be monitored continuously.

1.5 PROJECT OBJECTIVES

The following objectives were developed:

For Strategic and Developmental Activities:

(i) *To facilitate the process of participation and community ownership of the project.* A participatory approach was used in order to enable people to share, plan, act, learn, monitor and evaluate their own development. The ultimate aim of the objective was to pass on the control and responsibilities of the project to the farming community. This process continued over several growing seasons and therefore required long-term commitment from both the farming community and the change agents, which in the case of Mlondozi were the MDACE and ARC-ISCW.

(ii) To increase community awareness and understanding of the benefits and costs of natural resource conservation and to promote their input to implement conservation measures.

(iii) *To train farmers and Extension Officers in the skills necessary to sustainably implement and manage the Mlondozi Landcare project.* The main aim was not only the “transfer of knowledge” but involving farmers in their own development and incorporating their indigenous knowledge into the farming system.

(iv) *To monitor and evaluate the profitability and sustainability of farming systems development in the Mlondozi Landcare project.* The primary aims of monitoring were to provide a basis for decisions on subsequent stages of the research or development, to formulate judgments on performance, and to contribute to accountability for the use of resources. To do this required the development of clear sets of objectives and indicators of success, which would promote accountability and participation and which could be monitored and evaluated by the relevant decision-makers at all levels. For this purpose participatory and systems-based evaluation models were used, which helped to facilitate the implementation of the monitoring and evaluation processes.

For Research:

(v) To monitor the effects of liming on the neutralization of soil acidity and to determine the re-acidification rate of soils under cultivation.

(vi) To measure the effects of liming on growth and yield of maize.

(vii) To determine the relative importance of soil properties in determining the soil buffer capacity of the major soil groups.

(viii) To determine the mechanism that governs soil acidification, estimate soil acidification rates of the major soil groups and make recommendations and set guidelines for efficient lime application rates to ensure sustainable land use.

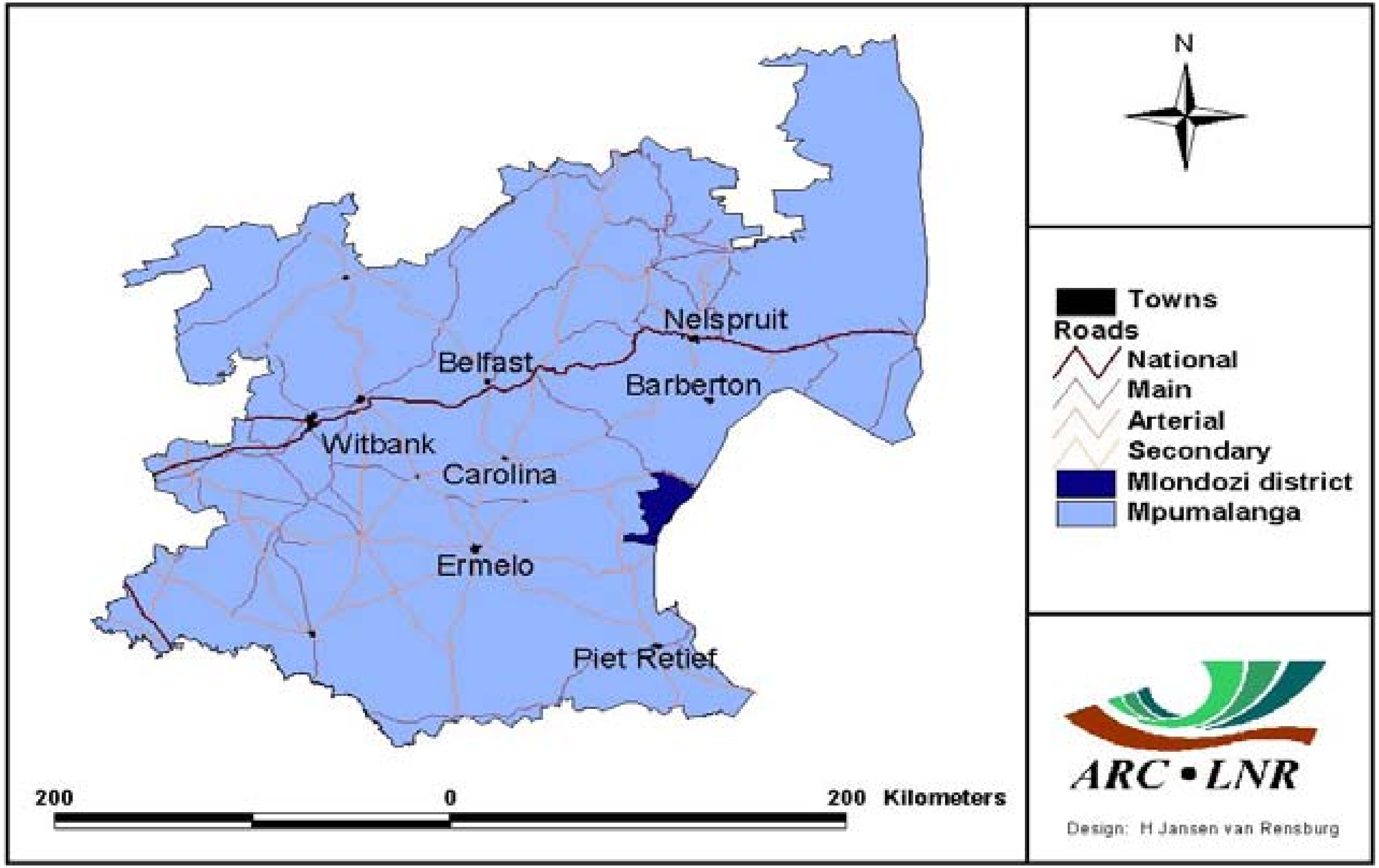
Objectives v to viii formed the basis of the present study and will be discussed in detail in **Chapters 2 to 7.**

1.6 STUDY AREA

1.6.1 Locality and physical features

The study area (Mlondozi district) is located in the Mpumalanga Province (Map 1.1) and is situated between 26º 05' and 26º30' S and 30º44' and 31º00' E and occupies a total area of 54 000 ha. The district is bordered by Swaziland towards the east; the Oshoek road in the North and the municipal borders of the town Amsterdam in the south.

The district is extremely hilly with altitudes varying from 1 700 m in the north, dropping to 1 300 m centrally and rising to 1 580 m above sea level in the south. The hydrology is characterized by a number of smaller streams from tributaries of the Mpuluzi River, which drains from west to east, flowing into the Usutu River in Swaziland. The larger tributaries are the Swartwater and Metula rivers. Wetlands occur in the northern portion of the district mainly in the vicinity of Belvedere settlement (Myburgh & Breytenbach, 2001).



Map 1.1 Map of study area location in the Mpumalanga Province.

1.6.2 Climate

The Mlondozi district forms part of the Highveld climatic region, which receives an annual average precipitation of between 650 mm in the west to 900 mm on its eastern border (Myburgh & Breytenbach, 2001). Long-term weather station data for Athole (26°36' S and 30°35' E) and Oshoek (26°13' S and 30°59' E) are summarized in Table 1.1. The long-term annual rainfall recorded at the Athole weather station varies between 893 to 992 mm from north to south in the district. The seasonal distribution is uneven. The summer season (October to March) receives on average 83% of the total rainfall, while the winter season (April to September) receives only 17% of the rainfall. The air temperature is subject to large seasonal and daily variation. Monthly average daily temperature ranges from 10.2 ºC for the coldest month (June) to 18.9 ºC for the hottest month (January/February).

In general it can be stated that maize, the main crop being produced in the area, is a warm weather crop and is not suitable to be grown in areas where the mean daily temperature is less than 19 ºC or where the mean of the summer months is less than 23 ºC (Du Plessis, 2003).

1.6.3 Geology and soils

The geology of the area is homogeneous, mostly underlain by quartz monzonite of the Mpuluzi Granite formation (Myburgh & Breytenbach, 2001). The study area is characterized by highly acidic soils and soils with humic characteristics are common. A soil survey done by Booyens *et al.* (2000), using Soil Classification – A Taxonomic System for South Africa (Soil Classification Working Group, 1991) found that the soil forms in the intensively cultivated areas are dominated by distrofic yellow apedal soils belonging to the Clovelly (Xantic Ferralsols) and Magwa (Humic Ferralsols; FAO-ISS-ISRIC, 1998) soil forms (Map 1.2). The Clovelly soil form is characterized by an A-horizon yellowish in colour, weak in structure without water stagnation, underlain by yellow-brown, structureless, sandy clay subsoil. Magwa soil form is characterized by a humic A-horizon underlain by yellow-brown, structureless subsoil.

The subdominant soil forms in the district consist of dystrophic red apedal soils, Hutton (Rhodic Ferralsols) and Inanda (Humic Umbrisols; FAO-ISS-ISRIC, 1998) as indicated in Map 1.2. The Hutton soil form is characterized by a reddish coloured, weak structure in which water stagnation does not take place. The rest of the district is dominated by Mispah (Dystric Leptosols; FAO-ISS-ISRIC, 1998) soils, shallow soils underlain by a hard rock layer, and rock outcrops (Booyens *et al.*, 2000).

Table 1.1 Climatic summary for the Athole and Oshoek weather stations, situated respectively 10 km to the south and to the north of the Mlondozi district (Agromet, 2002)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave/*Total values	Years
AveT[1]	18.9	18.9	17.8	15.3	12.7	10.2	10.4	12.9	15.8	17.4	18.0	18.8	15.6	45
MaxT[1]	23.8	23.6	23.0	21.6	19.5	17.2	17.6	19.9	22.4	22.9	23.2	24.0	21.6	55
AveX[1]	29.5	28.9	28.2	26.6	24.3	22.3	23.0	26.5	30.0	30.7	29.5	29.6	27.4	45
MinT[1]	12.9	13.0	12.0	9.5	6.3	3.4	3.2	5.0	8.0	10.0	11.4	12.6	9.0	55
AveN[1]	8.3	8.9	7.5	3.9	1.1	-2.0	-2.3	-0.7	1.5	4.1	6.4	7.9	3.7	45
Rain[1]	167.0	146.8	100.5	51.8	17.5	14.1	10.3	15.8	45.4	107.2	139.5	175.6	*992	64
Rain[2]	145.7	119.7	105.7	49.8	36.1	10.3	9.1	15.6	37.2	100.7	134.4	128.1	*893	36
HU[1]	260.5	233.2	232.3	167.8	97.0	34.9	39.3	91.3	163.6	201.0	219.8	257.1	*1998	45
Suns[1]	7.2	7.1	7.2	7.2	7.7	7.3	7.7	8.2	7.6	7.0	6.8	7.2	7.4	22
Evap[1]	180.3	149.2	152.1	134.3	138.2	126.6	139.7	168.0	189.2	182.6	177.8	191.8	*1930	24
Heat units (October to March)				1 403.9			**Heat units (April to September)**					593.9		
Earliest frost date				7 January			**Latest frost date**					24 September		
Mean first date of frost				14 June			**Mean last date of frost**					17 August		
Mean frost season length				64 days										

1 Athole weather station

2 Oshoek weather station

AveT: Average temperature (degrees °C)

MaxT: Maximum temperature (degrees °C)

AveX: Average of the one highest MaxT per month (degrees °C)

MinT: Minimum temperature (degrees °C)

AveN: Average of the one lowest Min T per month (degrees °C)

Rain: Total rainfall (mm)

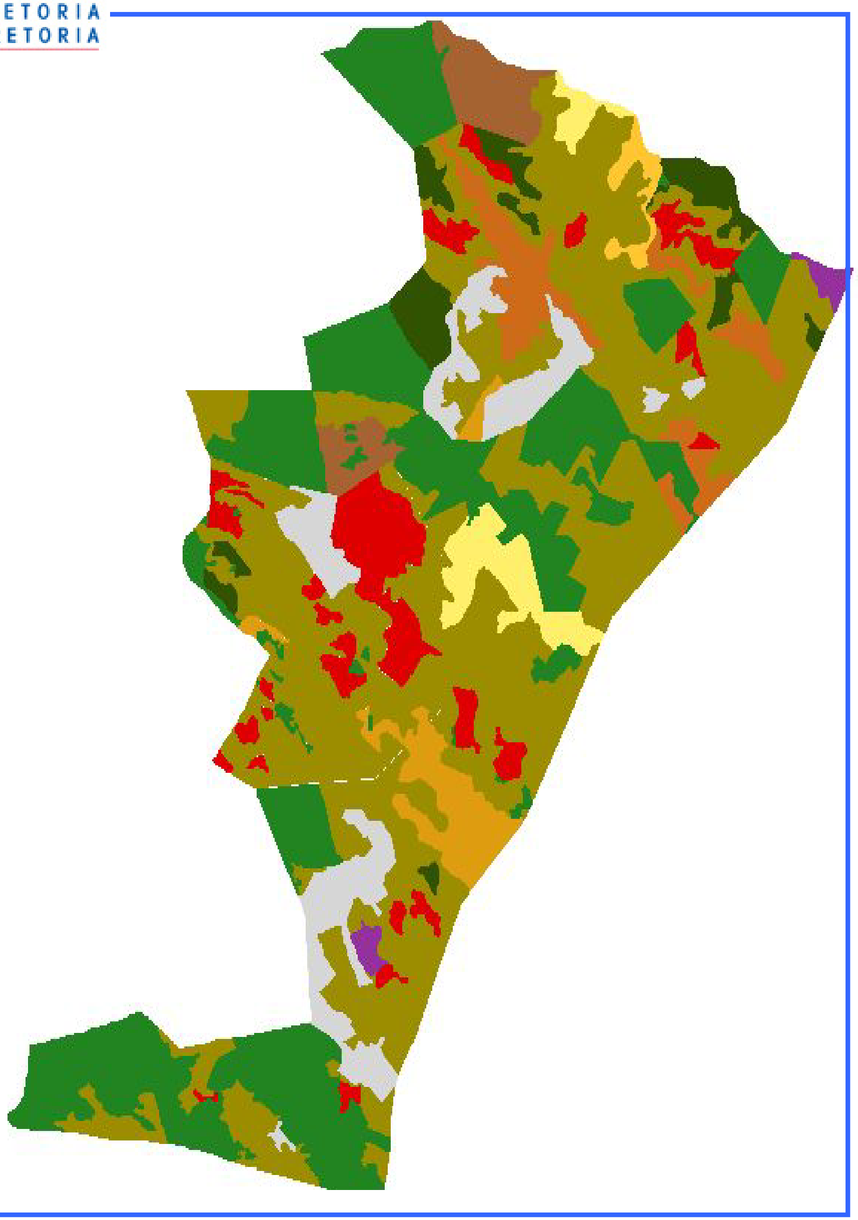
Evap: Evaporation, A-pan (mm)

HU: Heat units above 10°C

Suns: Sunshine hours, Daily, Campbell-Stokes

SOIL LEGEND

Map unit	Dominant soil forms		Depth (m)	Subdominant soil forms
	SA soil classification	FAO		
🟪	Magwa 1100 Clovelly 1100	Humic Ferralsols Xanthic Ferralsols	0.3-0.6	Mispah, Glenrosa
🟥	Magwa 1100 Clovelly 1100	Humic Ferralsols Xanthic Ferralsols	0.6-0.9	Avalon, Kroonstad, Katspruit, Mispah, Longlands, Glencoe, Pinedene, Oakleaf, Glenrosa
🟨	Magwa 1100 Clovelly 1100 Inanda 1100 0	Humic Ferralsols Xanthic Ferralsols Humic Umbrisols	0.6-0.9	Kroonstad, Avalon, Mispah, Longlands, Oakleaf, Glenrosa
🟧	Magwa 1100 Clovelly 1100	Humic Ferralsols Xanthic Ferralsols	0.6-0.9	Avalon, Kroonstad, Katspruit, Longlands, Hutton, Inanda
🟩	Magwa 1100 Clovelly 1100	Humic Ferralsols Xanthic Ferralsols	>0.9	Avalon, Kroonstad, Katspruit, Mispah, Glenrosa
🟧	Magwa 1100 Clovelly 1100 Inanda 1100 Hutton 1100	Humic Ferralsols Xanthic Ferralsols Rhodic Ferralsols Humic Umbrisols	>0.9	Kroonstad, Avalon, Mispah, Longlands, Oakleaf, Katspruit, Glenrosa
🟨	Magwa 1100 Clovelly 1100	Humic Ferralsols Xanthic Ferralsols	>0.9	Avalon, Inanda, Hutton, Kroonstad, Katspruit, Mispah
🟥	Magwa 1100 Clovelly 1100	Humic Ferralsols Xanthic Ferralsols	0.3-1.5	Avalon, Inanda, Hutton, Kroonstad, Katspruit, Mispah
🟫	Mispah	Dystric Leptosols	<0.3	Clovelly
🟩	Plantations			
⬜	Villages			



Map 1.2 Soil map of the Mlondozi district.

1.6.4 Vegetation

The study area occurs in the Grassland Biome and more specifically in Veld type 63 or Piet Retief Sourveld with a smaller intrusion of Veld type 57 in the north-eastern sandy Highveld (Acocks, 1988) in the northern portion (Myburgh & Breytenbach, 2001).

According to Myburgh and Breytenbach (2001) the rangeland is generally in a satisfactory to good condition. There is, however, a decline in the condition of the rangeland from north to south. The central and, especially, southern regions are being utilized more intensively than the northern regions. The declared invader *Acacia dealbata* is a serious problem and will inevitably impact negatively on the livestock production potential of the district (Acocks, 1988; Myburgh & Breytenbach, 2001).

1.6.5 Land use

The main land uses in Mlondozi are settlements, plantations, cultivated land and unimproved grasslands. It is estimated that villages constitute an estimated 3 553 ha (7%), whilst 13 497 ha (25%) of plantations occur in the district. The Mlondozi district has approximately 12 746 ha (24% of district) of potentially arable land of which only 5 619 ha is of high production potential. Currently only 4 000 ha of the arable land is being cultivated. The land tenure system is still that of Tribal Authority, which falls under the jurisdiction of the government. Land allocation is through the Tribal Authority. Although farmers can acquire land, it is becoming increasingly in short supply.

1.6.6 Demographic information

The study area forms part of the Albert Luthuli (MP301) municipality area with approximately 80 000 people of which more than 99% are African. Of these, around, 36 000 are male and 44 000 are female. The age group 16 to 35 represents 33% of the population and 4% of the population is 65 years and older. Twenty-one percent of the people 15 years and older is illiterate. Amongst those aged 15 to 65 years, 61% are unemployed. IsiZulu is spoken by 47% of the people followed by SiSwati (34%).

Out of the 13 012 households in the area only 42% live in a formal dwelling. Only 19% of the households use electricity for cooking, whilst only 7.4% of households have sanitation facilities. Water is available to only 7% of the district's population in the form of water piped to their dwellings. The area is characterized by subsistence-based farming and rangelands are generally community-owned and managed (Stats SA, 1996).

1.7 GENERAL STRUCTURE OF THE THESIS

The thesis comprises nine chapters. Chapters 2 to 7 are to be submitted as articles. In addition to these chapters an introduction (Chapter 1), general conclusions and recommendations (Chapter 8), and a comprehensive list of references (Chapter 9) are included.

2

AN EVALUATION OF LIME EFFECTS ON TEMPORAL CHANGES IN SOIL ACIDITY PROPERTIES AND MAIZE GRAIN YIELDS

2.1 INTRODUCTION

Excessive soil acidity reduces crop growth and yield and the need for liming to increase crop production is an accepted practice. However, the cost of liming makes the initial investment a daunting proposition for many farmers, especially resource-poor farmers. Large areas of agricultural land in South Africa that are being utilized by resource-poor farmers are situated in the former homelands that are still owned by government. The result is that land users are hesitant to make long-term investments and therefore seek information on the longevity of liming responses, as well as the rate and frequency of lime application. Coventry *et al.* (1997) found that wheat grain yield responded to 2.5 tonnes lime ha^{-1} for periods as long as 12 and 13 years after application in Victoria, Australia. Similar results were found by Scott *et al.* (1999) who reported a wheat grain yield response to limestone at 10 and 11 years after application. The long-term beneficial effects of lime, as reported by Coventry *et al.* (1997) and Scott *et al.* (1999), make the application of lime an economically sound investment. The residual effect of lime application is dependent on crop requirement, soil buffer capacity, nitrogen application rate, initial soil pH, and management philosophy (Helyar, 1976).

The present study was undertaken to evaluate the effect of liming on temporal changes in soil acidity properties and maize grain yield in a resource-poor farming area in the Mpumalanga province. The results obtained and lessons learned in the study were to serve as a guide to similar projects that would be executed in various resource-poor farming areas in South Africa. As part of the programme, dolomite was applied at a rate of 5 tonnes ha^{-1} to ≈ 4000 ha croplands in the district with a total financial assistance of R 2.5 million. For lime application strategies to be effective in resource-poor agriculture areas, reliable information on lime effects on soil acidity properties and maize grain yield is required. In particular, information is required on the effectiveness and frequency of lime application, as well as on critical soil acidity levels for yield optimization.

The objectives of the study were to evaluate (i) the temporal changes in soil acidity properties (pH, extractable acidity (Al^{3+} + H^+), extractable Al^{3+}, acid saturation), (ii) the residual benefit of lime application on maize grain yield, and (iii) critical soil acidity indices in two medium-term liming experiments in on-farm trials, in the Mlondozi district of Mpumalanga.

2.2 MATERIAL AND METHODS

2.2.1 Soils and experimental design

In 1997 and 1998, liming experiments planted to maize were initiated on two acid soils in the Mlondozi district of Mpumalanga, South Africa. Six and five-year trials were set up on a Hutton form, Hayfield family (Humic Ferralsol) and an Oakleaf form, Caledon family (Rhodic Cambisol; FAO-ISS-ISRIC, 1998), respectively (Table 2.1).

Table 2.1 Selected soil physical and chemical properties[1] of the topsoil (0-250 mm) of the two experimental sites prior to establishment of trials

	Experimental soil	
Soil form[2]	Hutton	Oakleaf
Soil family[2]	Hayfield	Caledon
Clay (< 2 µm) (%)	35.4	37.0
Clay mineralogy (%)[3]	Kt = 59, Qz=22, Go=19	Kt=60, Qz=23, Go=17
pH (H_2O)	5.44	4.57
pH (KCl)	4.50	3.95
Extractable Al ($cmol_c\ kg^{-1}$)	0.23	1.28
Extractable acidity ($cmol_c\ kg^{-1}$)	0.35	1.41
Acid saturation (%)	34	61
Ca ($cmol_c\ kg^{-1}$)	0.75	0.45
Mg ($cmol_c\ kg^{-1}$)	0.47	0.35
Organic C (%)	2.05	5.64
OM (%)[4]	3.53	9.70
Soil BC ($cmol_c\ kg^{-1}$ pH $unit^{-1}$)	0.65	2.49
Soil BC ($kmol_c\ (ha_{10cm})^{-1}$ pH $unit^{-1}$)	8.42	32.42

1 According to the The Non-Affiliated Soil Analysis Work Committee (1990)
2 Soil Classification Working Group (1991)
3 Clay minerals listed in order of decreasing abundance: Kt=Kaolinite, Qz=Quartz, Go=Goethite
4 Organic matter % = 1.72 x % C (Jackson, 1958)

Treatments comprised factorial combinations of lime (three treatments) and fertilizer (two treatments), which were arranged in a randomized block design with three replicates (3 x 2 x 3 = 18 plots) separated by 5 m pathways. Fertilizer treatments consisted of a control (zero fertilizer), and a mixture of 30 kg N ha^{-1}, 25 kg P ha^{-1} and 30 kg K ha^{-1} at planting, plus 50 kg N ha^{-1} in the form of limestone ammonium nitrate as a topdressing eight weeks after planting. The fertilizer was band-placed at annual planting. The lime treatments consisted of a control (zero lime), 5 and 10 tonnes of dolomitic lime ha^{-1}. The lime was broadcast (once-off application in September 1997 and 1998) prior to planting, and ploughed in to a depth of approximately 300 mm. Lime application rates were selected to complement a lime subsidy of 5 tonnes ha^{-1} from the National Department of Agriculture that started in 1997. A quality analysis of the lime used in the study is given in Table 2.2.

Table 2.2 Quality analysis values by calcium carbonate equivalent and resin suspension method of the experimental lime

	%
$CaCO_3$	43.65
$MgCO_3$	41.03
Total ($CaCO_3$ + $MgCO_3$)	84.68
CCE[1] neutralizing value	86.90
Resin neutralizing value (RH)[2]	84.08

1 CCE = Calcium carbonate equivalent

2 Resin method (Bornman *et al.*, 1988)

The individual plots were 9.25 m x 3.6 m (33.3 m^2) in size consisting of four rows each of maize. Only the middle two rows (length = 7.2 m) were used for data collection, with sampling borders of 1 m on each side.

2.2.2 Soils sampling and analysis

Topsoil samples (0 - 250 mm) were taken annually in March. Eight soil samples were taken within each plot between the rows and a composite sample was made up. Samples were air-dried and ground to pass a 2 mm sieve.

Soil pH (H_2O) was determined in a 1:2.5 (soil:water) suspension (Reeuwijk, 2002). The Walkley-Black method was used for the determination of organic carbon (Walkley & Black, 1934). Extractable acidity (H + Al) was determined by extraction 1 M KCl and titration with 0.1 M NaOH. Extractable Al was determined in the same extract by adding 10 cm^3 NaF to the titrate. These extractions can be regarded as a measure of extractable acidity and Al (The Non-Affiliated Soil Work Committee, 1990). Acid saturation was determined as the ratio of extractable acidity (Al + H) to the sum of extractable Ca, Mg, K, Na and extractable acidity (Al + H), expressed as a percentage. To determine the soil buffer capacity (soil BC) of the experimental soils, potentiometric titrations (Ponizovskiy & Pampura, 1993) were performed on soil samples that were equilibrated overnight with 1 M KCl. The soil BC was calculated as reported by Bache (1988).

2.2.3 Planting and yield estimates

Maize seed of cultivar CRN 3631 was hand-planted annually under a dryland farming system at the end of October, using a row spacing of 0.91 m. The plant population density at planting was 55 000 plants ha^{-1}, which was thinned out to approximately 35 000 plants ha^{-1}.

The trials were harvested annually in May. The seed mass and moisture content were determined and final seed yields were adjusted to 12.5% moisture content. Trial management was done in a collaborative research-farmer initiative. Maize yields could not be determined for the years 2001 and 2003 in the Oakleaf soil form because the trials were harvested by the farmer before yields could be determined in 2001 and livestock entered the trial area and grazed on the maize grain in 2003. All trials were farmer managed with assistance from ARC personnel.

The evaluation of critical threshold values for soil acidity indices was based on relative grain yield values. The advantages and shortcomings of the relative yield concept were discussed by Bray (1944) and Van Biljon *et al.* (2008), but the conclusion was that applying the relative yield concept to field data makes it possible to include results from different climatic zones, soil types, maize cultivars, plant spacing and seasons. Relative grain yield per plot was obtained by expressing absolute yield as a percentage of the mean of the highest yielding treatment. Averages were calculated from the replicate values to represent the relative grain yield per treatment.

2.2.4 Rainfall data

Rainfall data for the Athole (26°36’ S and 30°35’ E) weather station are summarized in Table 2.3, at an approximate distance of 10 and 15 km from the trial sites.

The total annual rainfall varied from 595 mm for the 2002/03 season to 1250 mm for the 1999/2000 season. The long-term total for the district is characterized by an uneven rainfall distribution. The summer season (October to March) receives on average 84% (mean of 728 mm over six years) of the total rainfall, while the winter season (April to September) receives only 16%.

Table 2.3 Mean monthly rainfall data (mm) for the Athole weather station situated 10 km to the south of the Mlondozi district (Agromet, 2008)

Season	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1997/1998	23	7	16	54	147	182	109	99	65	182	49	5	936
1998/1999	0	2	7	72	134	117	236	128	72	36	13	15	832
1999/2000	6	4	9	34	99	100	361	208	240	94	44	51	1250
2000/2001	30	12	15	53	71	220	174	92	114	67	131	12	991
2001/2002	6	3	0	16	90	219	89	37	74	40	53	3	667
2002/2003	16	19	40	30	69	74	104	135	59	31	12	6	595
64-year mean	14	10	16	45	107	140	176	167	147	101	52	18	992

2.2.5 Statistical analysis

Data were analyzed using the Genstat statistical program (Genstat, 2003). The values that will be discussed are replicate means across fertilizer levels and per lime application level in order to evaluate the main effect of lime application. The effect of liming on soil acidity properties and maize grain yield was evaluated by analysis of variance (ANOVA). The Bonferroni multiple comparison test for means separation was used to test all main effects at the 5% probability level (Table 2.4).

Table 2.4 ANOVA table of probabilities of treatment effects on soil pH (H_2O), extractable (H+Al), Al, acid saturation, organic C and maize grain yield for the Hutton and Oakleaf soil forms

Variable	Hutton		Oakleaf	
	F-ratio			
	Lime	Year x Lime	Lime	Year x Lime
pH (H_2O)	205.33***	1.99*	0.32***	0.52ns
Extractable (H+Al)	195.51***	6.69***	42.77***	2.01*
Extractable Al	351.28***	56.86***	37.47***	2.68*
Acid saturation	195.51***	6.69***	47.22***	1.90ns
Maize grain yield	5.22**	1.29ns	33.09***	3.58*

*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$ and ns = not significant

Pearson's coefficient of correlation was calculated between measured variants (Rayner, 1969). Non-linear regression results were analyzed by using the broken-stick model, whereby two straight line segments (a split-line or broken-stick model) are fitted to the data (Genstat, 2003).

The broken-stick model was used to identify critical soil acidity levels where a significant decrease in absolute or relative yield, respectively could be expected.

2.3 Results and discussions

The values that will be discussed are replicate means across fertilizer levels and per lime application level in order to evaluate the main effect of lime application.

2.3.1 Soil pH, extractable acidity, Al and acid saturation

Temporal changes in soil acidity parameters at different lime application rates for the experimental soils are shown in Table 2.5.

Hutton soil form: Liming had a highly significant ($P<0.001$) effect on all soil acidity parameters (Table 2.4). A significant interaction between lime and seasons after lime application was recorded for all soil acidity parameters (Table 2.4). In the first season, lime significantly ($P<0.05$) increased soil pH (H_2O) by 0.60 and 0.75 pH units in the 5 and 10 tonnes lime ha^{-1} treatments, respectively (Table 2.5). The reported optimal pH (H_2O) for maize production, namely 5.5 to 6.5 (Buys, 1986), was attained for both the 5 and 10 tonnes lime ha^{-1} applications within the first season of lime application. A continued significant ($P<0.05$) increase in soil pH (H_2O) was recorded until the highest values of 6.21 and 6.57 were reached within three seasons after liming in the 5 and 10 tonnes lime ha^{-1} rates, respectively. This time lag of three years found between the lime application and the attainment of maximum soil pH (H_2O) can be attributed to the relatively slow reactivity of the dolomitic lime that was used. A similar lack in equilibrium between free limestone and the soil mass was found by Walker (1953) and Bolton (1972, 1977).

The pH (H_2O) data in the highest lime treatment showed a significant ($P<0.05$) increase over the 5 tonnes lime ha^{-1} treatment for the last four years of the trial. The Hutton soil continued to show significantly ($P<0.05$) higher soil pH (H_2O) values due to lime after 6 years, where the 5 and 10 tonnes lime ha^{-1} rates resulted in 1.01 and 1.47 pH unit increases, respectively, over the unlimed treatment. This indicates that the beneficial effect of lime persisted for at least 6 years after application under the specific production practice that was used. Extractable acidity and Al, and acid saturation decreased ($P<0.001$) with lime application (Table 2.4). In the first season after liming, the initial extractable acidity, Al and acid saturation levels of 0.34, 0.21 $cmol_c$ kg^{-1} and 21.5%, respectively, were significantly decreased ($P<0.001$) to near zero levels, with 5 and 10 tonnes lime ha^{-1} application (Table 2.5). The residual effect of lime in reducing the values of the various soil acidity properties to near zero levels was observed for at least 6 years after the once-off lime application in 1997.

Table 2.5: Changes in soil pH (H_2O), extractable acidity, Al and acid saturation as affected by lime (tonnes ha^{-1}) in the Hutton and Oakleaf soil forms over time

Year	Hutton												Oakleaf											
	pH (H_2O)			(H+Al)			Al			Acid sat.			pH (H_2O)			(H+Al)			Al			Acid sat.		
	0	5	10	0	5	10	0	5	10	0	5	10	0	5	10	0	5	10	0	5	10	0	5	10
1998	5.22^{b}	5.82^{c}	5.97^{cd}	0.34^{b}	0.04^{cd}	0.05^{d}	0.21^{b}	0.09^{cd}	0.06^{cd}	21.5^{c}	2.5^{e}	2.4^{e}	-	-	-	-	-	-	-	-	-	-	-	-
1999	5.15^{ab}	5.95^{cd}	6.17^{de}	0.39^{b}	0.02^{cd}	0.00^{d}	0.25^{b}	0.02^{d}	0.00^{d}	22.4^{c}	0.6^{e}	0.0^{e}	4.18^{ab}	4.59^{bc}	4.94^{bc}	1.40^{bc}	0.95^{de}	0.62^{e}	1.28^{bc}	0.83^{cde}	0.52^{e}	74.2^{a}	39.9^{cd}	16.7^{e}
2000	5.34^{b}	6.21^{de}	6.57^{f}	0.20^{bc}	0.00^{d}	0.00^{d}	0.14^{bc}	0.01^{d}	0.00^{d}	11.8^{d}	0.0^{e}	0.0^{e}	3.83^{a}	4.82^{abc}	5.04^{d}	1.05^{cd}	0.77^{e}	0.73^{e}	0.71^{de}	0.60^{e}	0.57^{e}	62.7^{ab}	34.3^{de}	32.7^{de}
2001	5.01^{a}	5.96^{cd}	6.31^{ef}	0.64^{a}	0.02^{cd}	0.00^{d}	0.21^{b}	0.04^{cd}	0.00^{d}	31.1^{b}	0.9^{e}	0.0^{e}	4.40^{abc}	4.79^{abc}	4.94^{cd}	2.35^{a}	1.67^{b}	1.24^{cd}	2.11^{a}	1.48^{b}	1.09^{bcd}	76.6^{a}	53.3^{bc}	36.3^{cd}
2002	4.87^{a}	5.96^{cd}	6.44^{ef}	0.69^{a}	0.02^{cd}	0.00^{d}	0.67^{a}	0.02^{d}	0.00^{d}	37.3^{ab}	1.1^{e}	0.0^{e}	4.25^{abc}	4.45^{abc}	4.79^{bc}	2.32^{a}	2.18^{a}	1.29^{bcd}	2.26^{a}	2.11^{a}	1.06^{bc}	77.3^{a}	75.1^{a}	40.8^{cd}
2003	5.00^{a}	6.01^{cd}	6.47^{ef}	0.77^{a}	0.09^{cd}	0.02^{cd}	0.72^{a}	0.07^{cd}	0.02^{d}	39.4^{a}	3.2^{e}	0.7^{e}	4.37^{abc}	4.54^{abc}	4.98^{bc}	2.36^{a}	2.00^{a}	1.23^{cd}	2.33^{a}	1.95^{a}	1.17^{bc}	75.6^{a}	70.7^{ab}	40.9^{cd}
LSD	0.30			0.14			0.11			8.3			0.72 (ns)			0.42			0.45			18.3 (ns)		

Column and row values having the same symbols are not statistically different at $P = 0.05$

Oakleaf soil form: Lime significantly increased ($P<0.001$) soil pH and decreased extractable acidity and Al, and acid saturation (Table 2.4), but a significant ($P<0.05$) interaction between lime and seasons after lime application was only recorded for extractable acidity and Al. In the first season a non-significant increase in soil pH (H_2O) from an initial pH (H_2O) of 4.18, to 4.59 and 4.94, in the 5 and 10 tonnes lime ha^{-1} treatments, respectively, was found (Tables 2.4 and 2.5). However, the application of lime did not succeed in raising the soil pH to the optimum range (5.5 to 6.5) recommended for maize production (Buys, 1986). Maximum pH (H_2O) values were recorded in the second season after lime application, with only the 10 tonnes lime ha^{-1} treatment being significantly higher than the unlimed treatment.

Significant ($P<0.05$) decreases in extractable acidity and Al, and acid saturation, especially in the 10 tonnes lime ha^{-1} treatment, were observed in the first season after liming (Table 2.5). Although these values were much lower than the control, only the 10 tonnes lime rate decreased acid saturation levels to below 20%. As with soil pH (H_2O), the lime application was not sufficient to decrease extractable acidity, Al and acid saturation to threshold values recommended for maize production.

Comparison of the experimental soils: The two soils clearly reacted differently towards lime applications. An important contributing factor is the difference in soil buffer capacity (soil BC) between the two soils. Although this aspect will be dealt with in a subsequent article, it is important to mention that the soil BC for the Hutton and Oakleaf soils was 0.65 and 2.49 cmol$_c$ kg^{-1} pH unit^{-1}, respectively (Table 2.1). This implies that the Oakleaf soil form will have the greatest resistance to change and, therefore, larger amounts of lime will need to be applied to efficiently control excess soil acidity.

2.3.2 Grain yield versus lime application

Hutton soil form: Yield responses obtained during the first six seasons showed that the grain yield was significantly ($P<0.01$) affected by lime application (Tables 2.4 and 2.6). Liming resulted in a mean improvement in grain yield in the first season after liming of 0.68 and 0.91 tonnes ha^{-1}, respectively, in the 5 and 10 tonnes lime treatments (Table 2.6).

The results furthermore show that the application of 10 tonnes lime ha^{-1} did not result in a statistically significant increase in maize grain yield, indicating that a lime application rate of 5 tonnes lime ha^{-1} is advisable in the Hutton soil form. Although a poor linear correlation was found between absolute grain yield and lime application, a positive correlation ($P<0.05$) existed between relative yield and lime application (Table 2.7).

Table 2.6 Changes in absolute maize grain yield (tonnes ha^{-1}) as affected by lime (tonnes ha^{-1}) in the Hutton and Oakleaf soil forms over time

Year	**Hutton**			**Oakleaf**		
	Lime application (tonnes ha^{-1})					
	0	**5**	**10**	**0**	**5**	**10**
1998[1]	2.59**cdef**	3.27**fg**	3.50**g**	-	-	-
1999	2.79**def**	3.69**g**	3.69**g**	0.66**abc**	1.48**de**	1.64**e**
2000	1.39**a**	1.80**abc**	2.42**cdef**	0.11**a**	0.78**b**	1.39**de**
2001	2.34**bcde**	3.06**efg**	3.14**efg**	-	-	-
2002	2.05**abcd**	2.58**cdef**	2.59**cdef**	0.25**ab**	0.12**a**	0.94**cd**
2003	1.51**ab**	1.97**abcd**	2.14**abcd**	-	-	-
Mean[2]	2.25**a**	2.73**b**	2.78**b**	0.34**a**	0.79**b**	1.32**c**
$LSD_{(year\ x\ lime)}$[3]	0.890 ns			0.604		
$LSD_{(lime)}$[3]	0.363			0.349		

[1] Column and row values having the same symbols are not statistically different at P = 0.05

[2] Row values having the same symbols are not statistically different at P = 0.05

[3] LSD = Least significant differences of means (5% level), ns = not significant

Oakleaf soil form: Grain yield responded significantly to lime application (Tables 2.4 and 2.6). All lime treatments resulted in a highly significant ($P<0.001$) grain yield increase due to dolomite additions. Initially the effect of the 10 tonne lime treatment proved non significant compared to the 5 tonnes lime ha^{-1} rate. However, in the second season a significantly ($P<0.001$) higher yield (0.61 tonnes ha^{-1}) was observed in the 10 tonnes lime treatment (Table 2.6).

A statistically significant ($P<0.05$) decrease in grain yield for all treatments was observed over time (Tables 2.4 and 2.6). The detrimental effect of soil acidity is clearly illustrated by the yield results observed in the Oakleaf soil form trial. A strong relationship was furthermore obtained between lime rate and absolute ($P<0.05$) and relative ($P<0.05$) grain yields (Table 2.7).

Table 2.7 Pearson's coefficients of correlation (r) between different variants for the Hutton and Oakleaf soil forms

Variables	**Hutton**		**Oakleaf**	
	r	**P**	**r**	**P**
Absolute yield vs lime rate	0.417	ns	0.718	<0.05
Relative yield vs lime rate	0.529	<0.05	0.752	<0.05

ns = not significant

P = probability level

2.3.3 Absolute grain yield versus soil acidity properties

The values that will be discussed are pooled data per lime application level per experimental soils (Table 2.8).

Hutton soil form: Statistically significant relationships between absolute grain yield and pH (H_2O), extractable acidity and Al, and acid saturation, were observed, explaining 44.5, 26.5, 32.2 and 38.8 of the variation in yield, respectively (Table 2.8).

Table 2.8 Non-linear regression analysis between absolute yield and soil acidity properties for pooled data for the Hutton and Oakleaf soil forms

Variables	Hutton			Oakleaf		
	R^2 (%)	F	Critical value	R^2 (%)	F	Critical value
Yield vs pH (H_2O)	44.52	9.63**	5.19	73.47	19.38**	-
Yield vs extractable acidity	26.53	5.42*	0.045	65.37	13.21**	-
Yield vs extractable Al	32.17	6.64*	0.037	40.97	10.33**	-
Yield vs acid saturation	38.76	8.86**	2.50	73.47	19.38**	-

*** $P < 0.001$, ** $P < 0.01$, and * $P < 0.05$

Table 2.8 shows a significant positive correlation ($P<0.01$) between absolute grain yield and soil pH (H_2O) indicating an increase in yield with an increase in soil pH (H_2O). Furthermore, a statistically significant negative correlation was observed in Table 2.8 against absolute grain yield and extractable acidity ($P<0.05$) and Al ($P<0.05$), and acid saturation levels ($P<0.01$). This indicates that absolute yields significantly decrease with an increase in extractable acidity and Al, and acid saturation values (Table 2.8).

Maximum absolute grain yield was obtained between pH (H_2O) of 5.90 and 6.00, extractable acidity and extractable Al levels of zero. This indicates that further yield increase is unlikely to occur above a pH (H_2O) value of 6.00. Non-linear regression analysis was used to identify critical values for soil acidity indices where a reduction in absolute grain yield could be expected (Table 2.8). At a pH (H_2O) lower than 5.19 and an extractable acidity, extractable Al and acid saturation higher than 0.045, 0.037 $cmol_c\ kg^{-1}$ and 2.50%, respectively, a significant decrease in absolute yield occured (Table 2.8).

Oakleaf soil form: Fairly strong relationships between absolute grain yield and pH (H_2O), extractable acidity, extractable Al and acid saturation, were observed, explaining 73.5, 65.4, 40.9 and 73.5% of the variation in yield, respectively (Table 2.8). A highly significant positive relationship ($P<0.01$) is indicated between soil pH (H_2O) and absolute grain yield. However, the latter is highly significantly negatively correlated ($P<0.01$) with extractable acidity, extractable Al and acid saturation levels (Table 2.8).

Critical values for soil acidity indices could not be determined in the Oakleaf soil because soil acidity had not been successfully alleviated and therefore no plateau could be establish.

2.3.4 Relative grain yield versus soil acidity properties

The values discussed are once again pooled data per lime application level for both experimental soils. The reason behind pooling the data was to obtain a generalize data point taking into account seasonal and geographical variations. The relationships established between relative grain yield and soil acidity properties are shown in Table 2.9 and Figure 2.1.

Table 2.9 Non-linear regression analysis between relative yield and soil acidity properties for pooled data for the Hutton and Oakleaf soil forms

Variables	R^2 (%)	F	Critical value
Rel. yield vs pH (H_2O)	72.4	106.53***	5.491
Rel. yield vs extractable acidity	73.1	116.24***	0.277
Rel. yield vs extractable Al	72.0	118.52***	0.145
Rel. yield vs acid saturation	71.8	103.21***	13.003

*** $P < 0.001$, ** $P < 0.01$, and * $P < 0.05$

Compared to absolute grain yield, a marked improvement in the relationship between relative grain yield and soil pH (H_2O), extractable acidity, extractable Al and acid saturation were found (Table 2.9). Maximum relative yield was obtained at a soil pH (H_2O) of 6.25, an extractable acidity and Al of 0 $cmol_c\ kg^{-1}$, and an acid saturation of 0% (Figure 2.1). The optimum values for extractable acidity and Al, and acid saturation were similar to those for absolute grain yield, but the optimal soil pH (H_2O) was higher than that found for absolute yield.

Critical values where a decrease in relative grain yield could be expected were established at pH (H_2O) values lower than 5.49 and extractable acidity and Al, and acid saturation values higher than 0.277, 0.145 $cmol_c\ kg^{-1}$ and 13%, respectively (Table 2.9). These are critical thresholds where growth stress may be expected to occur in the Mlondozi district.

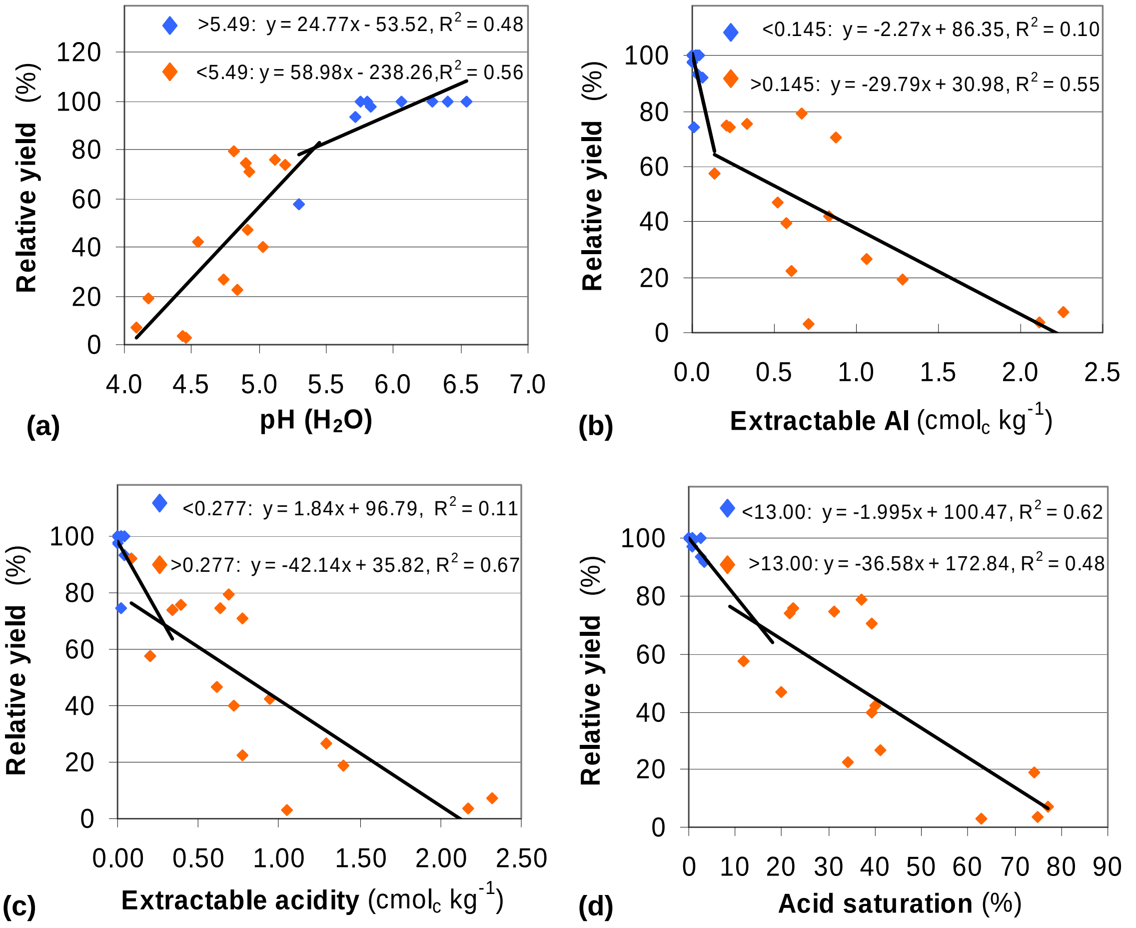


Figure 2.1 The relationships between relative grain yields and (a) soil pH (H_2O), (b) extractable Al, (c) extractable acidity and (d) acid saturation in all treatments of both experimental soils.

2.4 Conclusions

Temporal changes in soil acidity properties and maize grain yield were evaluated to quantify the longevity of lime application. The recommended level of 5 tonnes lime ha^{-1} increased soil pH (H_2O) to above 5.5 within one year of application in the Hutton soil. The longevity of liming (5 and 10 tonnes ha^{-1}) on surface soil pH (H_2O), relative to unlimed soil, extended for at least the 6 years that the trials were running. However, neither of the two lime application levels was sufficient to neutralize soil acidity in the Oakleaf soil. Within the first season after lime application, most of extractable acidity was neutralized even though the soil pH (H_2O) showed a lag period of 2 - 3 years before increasing. The Oakleaf soil showed the greatest resistance to change and larger amounts of lime need to be applied to bring about a given change in soil acidity properties in this soil compared to the Hutton soil. Measurements showed that the buffer capacity of the Oakleaf is much higher than that of the Hutton soil.

Furthermore, the residual benefit of liming on maize grain yield and the critical soil acidity indices at which a reduction in yield could be expected, were evaluated. Statistically significant increases in yield were found, following lime applications, in both experimental soils. Maximum absolute grain yield was obtained at a pH (H_2O) of between 5.90 and 6.00, extractable acidity and Al of 0 $cmol_c$ kg^{-1} soil and 0% acid saturation in the Hutton soil form. It is, therefore, suggested that yield increases are unlikely to occur above a pH (H_2O) value of 6.00. Critical thresholds in absolute yield for pH (H_2O), extractable acidity (Al + H) and Al, and acid saturation of 5.19, 0.045, 0.037 $cmol_c$ kg^{-1} and 2.50%, respectively, were recorded for absolute grain yield. Critical values for soil acidity indices could not be determined in the Oakleaf soil form because soil acidity had not been successfully alleviated. The critical thresholds when a reduction in relative yield was recorded were 5.49, 0.277, 0.145 $cmol_c$ kg $soil^{-1}$, 13% for pH (H_2O), extractable acidity (Al + H), Al and acid saturation, respectively. Monitoring extractable acidity annually, or every other year, in conjunction with soil pH is essential to assist in the management of on-farm soil acidity.