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ABSTRACT

An imperative of the South African government is to increase agricultural production in rural areas. In support of this, a project was initiated in the Mlondozi district of Mpumalanga Province under the National LandCare programme. The goal was to assess land management practices contributing to sustainable and profitable agricultural production. Medium-term liming experiments were sampled to a range of lime treatments in a Hutton and Oakleaf soil. Critical thresholds where a reduction in relative grain yield was found were at a pH (H_2O), extractable acidity, Al and acid saturation of 5.49, 0.277 $cmol_c$ kg $soil^{-1}$, 0.145 $cmol_c$ kg $soil^{-1}$ and 13%, respectively. Critical soil fertility threshold levels were established at 50 mg K kg^{-1}, 228-345 mg Ca kg^{-1}, 78-105 mg Mg kg^{-1} and 1.68-2.83 mg Cu kg^{-1}. Nutrient vector analysis showed a toxic build-up of Fe, followed by Al and to a lesser extent Mn, which depressed the uptake of Ca, Mg and B in the Hutton soil. In the Oakleaf soil, Al toxicity, followed by high concentrations of Mn and Fe, markedly reduced the uptake of Ca, Mg and K by maize. Net rates of acid production in the soil profile varied between 1.61 and 2.44 kmol H^+ ha^{-1} $year^{-1}$ for the Hutton soil and between 4.59 and 8.82 kmol H^+ ha^{-1} $year^{-1}$ in the Oakleaf soil due to liming. A decline of 0.046 pH unit $year^{-1}$ for an initial pH(H_2O) value of 5.33, and 0.140 pH unit $year^{-1}$ for an intial pH(H_2O) of 6.47, respectively, in the Hutton was recorded. For the Oakleaf these declines were 0.044 and 0.110 pH unit $year^{-1}$, from pH(H_2O) 4.54 and 5.15. Maintenance liming amounts at different pH values for the Hutton soil were equivalent to 0.2, 0.3 and 1.4 tonnes $CaCO_3$ ha^{-1} annually, while 0, 0.8 and 0.8 tonne $CaCO_3$ ha^{-1} annually were recorded for the Oakleaf soil.

The study was extended to 80 random topsoil samples in the district. Relationships of soil BC over limited pH ranges showed that at soil $BC_{(pH<4.5)}$ the main buffering mechanism was extractable Al > organic C > clay. At soil $BC_{(pH4.5-6.5)}$ the buffering mechanism was extractable Al > clay > CBD-Al > organic C > CBD-Fe. The main buffering mechanism between pH 6.5-8.5 was clay > CBD-Fe, organic C > CBD-Al. Acid production for 30 crop production sites varied from a measured 0.21 to 10.31 (mean 3.70) kmol H^+ ha^{-1} $year^{-1}$ The rate of pH decline for the top 0-250 mm depth was between 0.051 and 0.918 (mean 0.237) pH units $year^{-1}$. In the absence of remedial lime applications, pH (H_2O) values in most of the area are projected to decrease to the critical value of 5.68 or lower within 4 years. Soil with a pH (H_2O) value of >5.73, extractable Al and acidity of <0.18 and <0.25 $cmol_c$ kg^{-1} soil, respectively, clay content of ≤26%, and a ECEC value of ≤3.29 $cmol_c$ kg $soil^{-1}$, are at greater risk of acidification as gradual acceleration in soil acidification takes place at the above-mentioned critical thresholds.

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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.

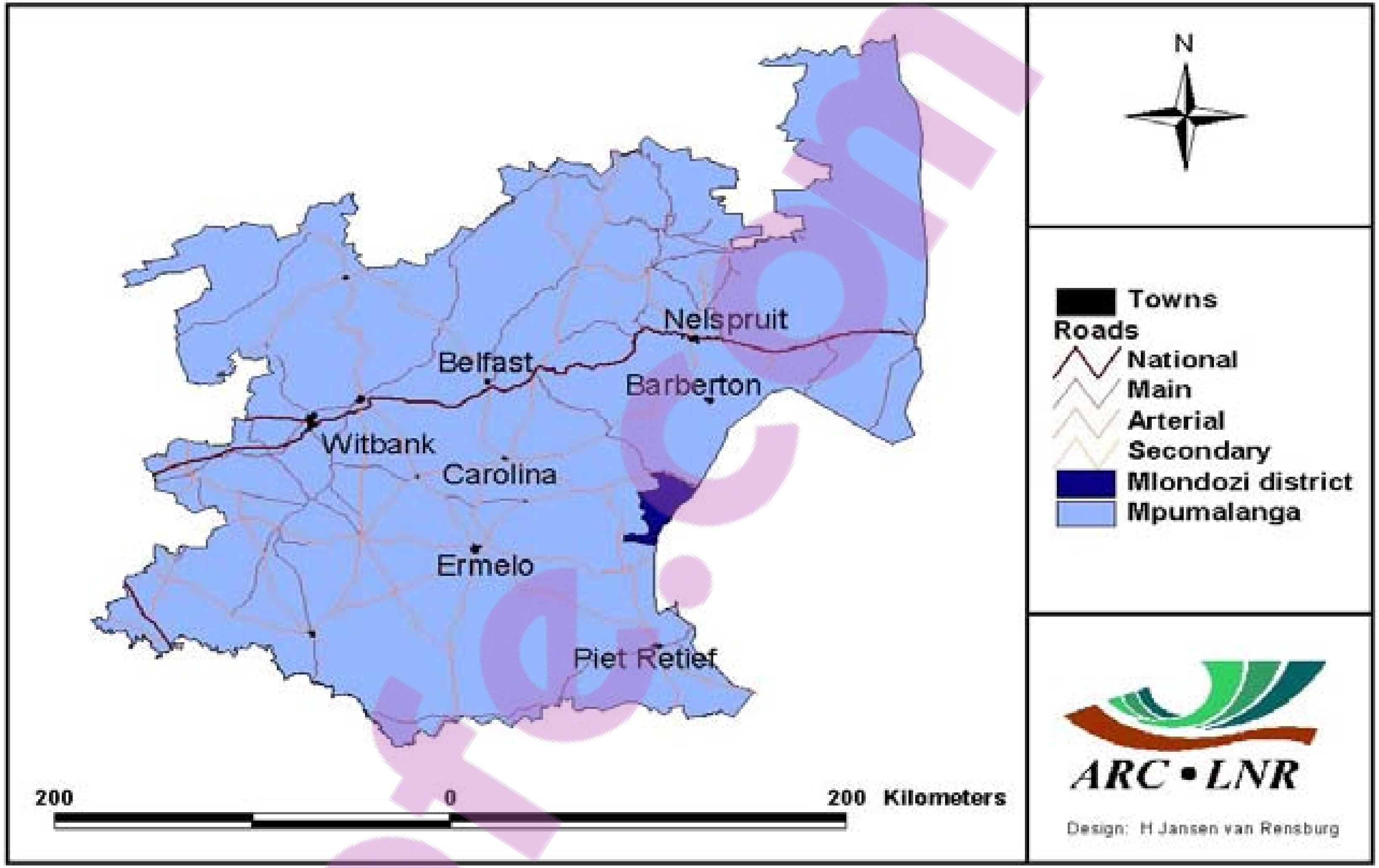
Objectives v to viii formed the basis of the present study and will be discussed in detail in **Chapters 2 to 7.**

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)

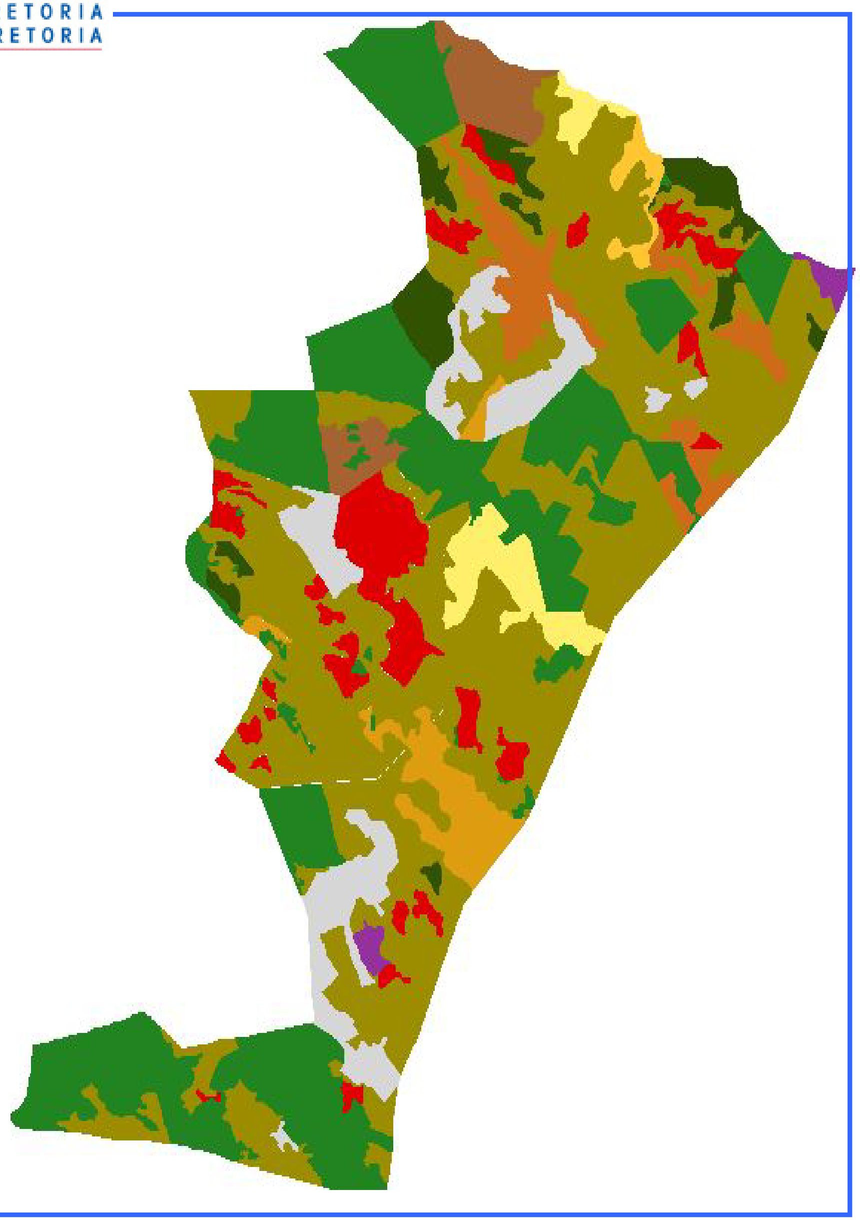
Evap: Evaporation, A-pan (mm)

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$_{\text{(year x lime)}}$[3]	0.890 ns			0.604		
LSD$_{\text{(lime)}}$[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.

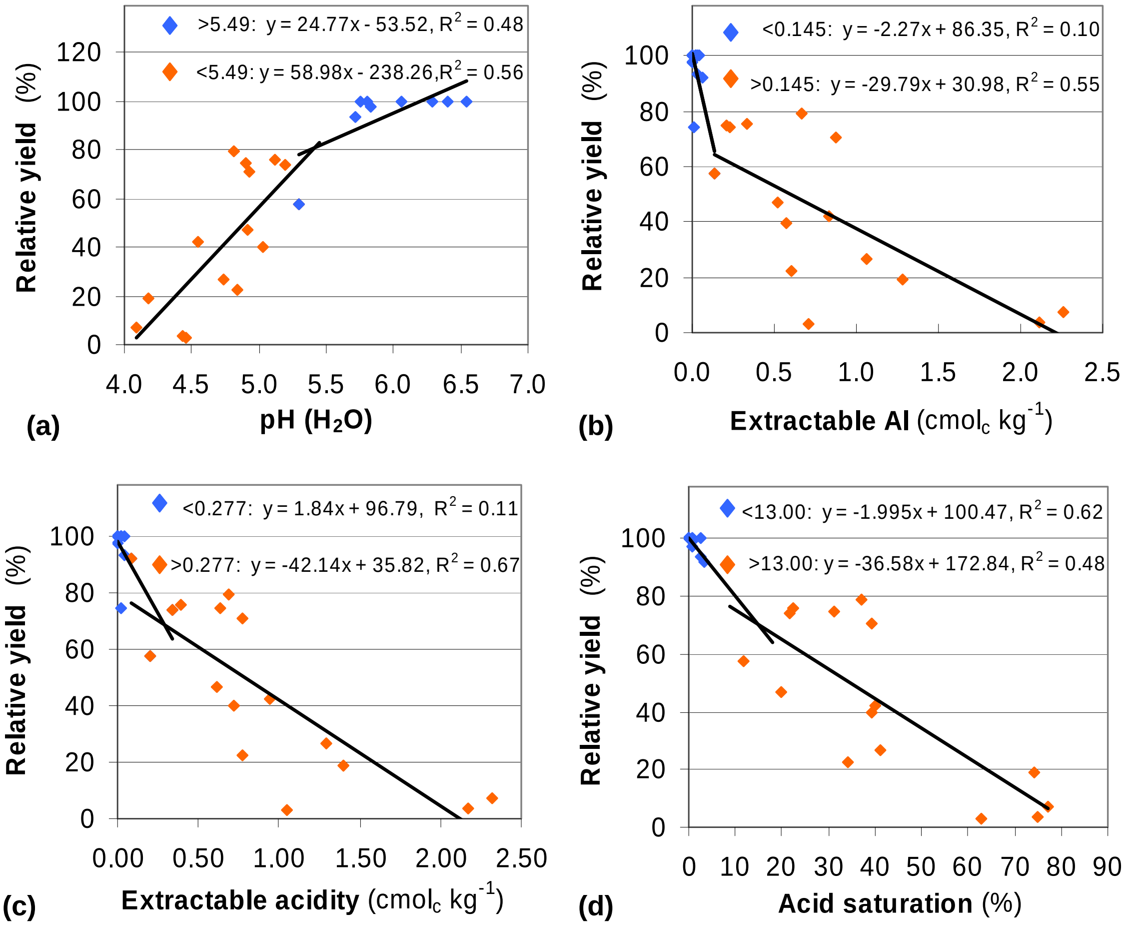


Figure 2.1 The relationships between relative grain yields and (a) soil pH (H_2O), (b) extractable Al, (c) extractable acidity and (d) acid saturation in all treatments of both experimental soils.

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.

3

THE EFFECT OF LIMING ON SOIL BUFFER CAPACITY, ACIDIFICATION RATES AND MAINTENANCE LIMING

3.1 INTRODUCTION

Although soil acidification is a natural process, modern agricultural practices have accelerated acidification of soils relative to natural ecosystem processes in many parts of the world (Singh *et al.*, 2003). Soil acidification is the result of proton production that occurs because of various natural biological and chemical processes in the soil. Most of these natural processes are buffered around pH 5.5 (H_2O) except under more severe leaching conditions, especially in more sandy soils. Apart from the natural processes, soil acidification is enhanced by losses of bases either by crop removal or leaching in the absence of an active root system, and the application of ammonical fertilizers (Singh *et al.,* 2003; Doerge & Gardner, 1985; Hart, 2002; Gasser, 1973). Regular liming is therefore required to balance the acidifying effect of these processes, and to ensure the efficient utilization of fertilizers by crops (Bolton, 1977). The effect of lime in raising soil pH extends beyond the first year after application, but predicted rates at which limed soils reacidify are often not known. The rate of these acidifying processes is slow under natural conditions, but generally accelerates under agricultural practices (Helyar & Porter, 1989). The rate at which any given production system acidifies is a function of the soil's buffer capacity, climate, and farming practice (Sumner & Noble, 2003). Magdoff *et al.* (1987) showed that the dominant soil properties contributing to a soil's pH buffering include the amount of organic matter and the quantity and type of clay minerals present. The buffer capacity of a soil may change over time due to a reduction in organic matter. This can lead to under or over predictions of proton production, especially in situations where the levels of organic matter changed dramatically over the study period.

The Australian Agriculture Assessment (2001) has shown that the soil acidification rates in Australia vary from an alkalizing farming system under tobacco production (-260 kg lime ha^{-1} year^{-1}) to strongly acidifying farming systems such as banana production (+2000 kg lime ha^{-1} year^{-1}), with an annual mean requirement of between 50 to 250 kg lime ha^{-1} year^{-1}. In the former case, net alkalinization is associated with approximately 70% of the nitrogen fertilizer being in the nitrate form. In contrast, the extremely high acidification rates recorded in banana production systems are a consequence of fertigation with high rates of ammonium-based fertilizers (average application rate of 508 kg N ha^{-1} year^{-1}), coupled with the removal of significant amounts of bases in both harvested product and pruning following bunch removal (Sumner & Noble, 2003). Annual soil acidification in South Africa may vary from less than 500 kg lime ha^{-1} $year^{-1}$ to 1500 kg lime ha^{-1} $year^{-1}$ and more (FSSA, 2003). This shows that soil acidification rates can vary quite dramatically between both soils and systems. It is therefore important that both the soil acidity status and estimates of the rate of acid production of soils are known, to facilitate corrective action by farmers.

Against this background the present study was undertaken in order to determine (i) the changes in soil buffer capacity, (ii) acid production loads, (iii) acidification rates, and (iv) maintenance lime requirements of two lime-amended soils in a resource-poor farming area.

3.2 MATERIALS AND METHODS

3.2.1 Experimental soils

The study was conducted on two acid soils in the Mlondozi district of Mpumalanga, South Africa. Two trials that were recorded for six and five years were laid out on Hutton (Humic Ferralsols) and Oakleaf (Rhodic Cambisols: FAO-ISS-ISRIC, 1998) soil forms, respectively (see Table 2.1 for chemical and physical analysis). A detail description of the experimental design was discussed in section 2.2.1.

3.2.2 Soil 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. The composite samples were air-dried and ground to pass through a 2 mm sieve.

Soil pH (H_2O) was determined in a 1:2.5 (soil:water) suspension using a combined calomel reference glass electrode and pH meter (Reeuwijk, 2002). Extractable acidity, (Al + H), and Al were determined in a 1 mol dm^{-3} KCl extractant. The ammonium acetate (1 mol dm^{-3}, pH 7) method was used to extract the cations Ca and Mg (Thomas, 1982). These cations were determined on an atomic absorption flame spectrophotometer (The Non-Affilliated Soil Analysis Work Committee, 1990). Acid saturation was determined as the ratio between extractable acidity and the sum of extractable Ca, Mg, K, Na and extractable acidity, expressed as a percentage.

3.2.3 Soil buffer capacity (soil BC)

Potentiometric titrations (Ponizovskiy & Pampura, 1993) were performed on samples that were equilibrated overnight with 1 M KCl. A 50 g soil sample was suspended in 100 ml 1 M KCl, stirred and left overnight. The suspension was titrated with 0.05 M NaOH whilst being stirred on a Metrohm potentiograph to a pH of 8.5. The titration rate was 0.667 ml min^{-1}. For each soil a linear regression function was fitted to the relationship between 0.05 M NaOH added and the soil. Equation 3.1, adapted from Bache (1988), was used to calculate soil buffer capacity (soil BC).

$$\text{Soil BC } (\text{cmol}_c \text{ kg}^{-1} \text{ soil pH unit}^{-1}) = \Delta(\text{OH}^-)/\ \Delta \text{ pH} \qquad [3.1]$$

where ΔpH is the change in pH (pH unit) due to the addition of OH^- ($cmol_c$ kg $soil^{-1}$) as NaOH.

The soil BC calculated in Equation 3.1 was converted to (kmol H^+ $(ha_{250\ mm})^{-1}$ $(pH\ unit)^{-1}$) using an average soil bulk density of 1300 kg m^{-3} using Equation 3.2 as suggested by Singh *et al*.(2003):

$$\text{Soil BC } [(\text{kmol H}^+ (\text{ha}_{250\text{ mm}})^{-1} (\text{pH unit})^{-1})] = (\text{BC x V x BD})/100\ 000 \qquad [3.2]$$

where V is volume of soil layer (m^3 ha^{-1}) to a depth of 250 mm; BD is bulk density (kg m^{-3}) and 100 000 to convert cmol (H^+) to kmol (H^+).

3.2.4 Acid production loads (APL) and acidification rates

Predicted acidification rates: The acid production load (kmol H^+ $(ha_{250mm})^{-1}$ $(year)^{-1}$) was calculated with Equation 3.3 as described by Helyar and Porter (1989):

$$\text{APL} = (\Delta\text{pH}/\Delta\text{t}) \text{ x soil BC} \qquad [3.3]$$

where ΔpH/Δt is the rate of pH decline (pH unit $year^{-1}$).

The decrease in soil pH in one year (pH $year^{-1}$) was calculated with Equation 3.4 as reported by Singh et al. (2003), using the APL and soil BC:

$$\Delta\text{pH units year}^{-1} = \text{APL/soil BC} \qquad [3.4]$$

The number of years required for a soil to reach a critical pH value where production losses are likely to occur was calculated as expressed by Hill (2003) in Equation 3.5:

$$\text{Time (years)} = [(\text{pH}_{(\text{current})} - \text{pH}_{(\text{critical})}) \text{ x (soil BC)}]/\text{APL} \qquad [3.5]$$

where $pH_{(current)}$ is the current pH, $pH_{(critical)}$ is the critical pH.

Measured acidification rates: Equation 3.6 as described by Doerge and Gardner (1985), was use to determine the measured annual change in soil pH. The use of pH (H_2O) as an indicator to predict acidification rates has been debated by many researchers (Walker, 1953; Bolton, 1977; Doerge & Gardner, 1985) because of the annual fluctuations in soil pH (Hart, 2002). According to Doerge and Gardner (1985) the sources and sinks of Ca^{2+} and Mg^{2+} are less complicated than those of H^+ and a high degree of correlation exists between soil hydrogen activity and basic cation saturation. Therefore the pH acidification rate (ΔpH unit $year^{-1}$) of a soil can be calculated if the relationship between pH and levels of extractable basic cations, and the measured annual change in basic cations are available (Doerge & Gardner, 1985). The annual change in soil pH was indirectly measured as the ratio between soil pH and levels of extractable basic cations, multiplied by the annual change in basic cations.

$$(\Delta \text{ pH}/\Delta \text{ [Ca + Mg]}) \times (\Delta \text{ Ca + Mg year}^{-1}) = \Delta \text{ pH year}^{-1} \qquad [3.6]$$

where Δ(Ca + Mg) is the change in soil (Ca + Mg) in mol_c kg^{-1} soil

3.2.5 Maintenance liming

Maintenance liming requirement was determined from the annual change in $Ca^{2+} + Mg^{2+}$ (Δ Ca + Mg $year^{-1}$) for the top 250 mm soil (Equation 3.7). This was achieved using the assumption that 1 mol of $CaCO_3$ neutralizes 2 mol of H^+ in the soil.

$$([\Delta(\text{Ca + Mg}) \text{ year}^{-1}] \times \text{BD} \times \text{V ha}^{-1} \times \text{CaCO}_3)/100\ 000 = \text{tonnes CaCO}_3 \text{ ha}^{-1} \text{ year}^{-1} \qquad [3.7]$$

where Δ(Ca + Mg) is the change in soil (Ca + Mg) in mol_c kg^{-1} soil; BD is the soil bulk density (kg m^{-3}); V the soil volume (m^{-3}) in the top 250 mm and $CaCO_3$ is 1 mol pure $CaCO_3$ (100.09 g $CaCO_3$ mol^{-1}).

3.2.6 Statistical analysis

The effect of liming on soil BC, APLs and acidification rates was evaluated statistically by analysis of variance (ANOVA) (Genstat, 2003). The Bonferroni multiple comparison test for means separation was used to test all main effects at the 5% probability level.

Pearson's correlations were calculated between measured pH changes and calculated acidification risk according to Equation 3.5 using Genstat (2003). Measured pH change is the rate of pH decline measured over 6 and 5 years (pH unit $year^{-1}$) in the Hutton and Oakleaf soil forms, respectively. The broken-stick analysis, a non-linear regression analysis, was used to evaluate critical pH ranges where a change in soil BC could be expected.

3.3 RESULTS AND DISCUSSION

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

3.3.1 Effect of lime application on soil BC

Hutton soil form: Liming had a highly significantly ($P<0.001$) decreasing effect on soil BC (Table 3.1 and 3.2).

Table 3.1 ANOVA table of probabilities of treatment effects on soil BC, acid production load, acidification rate and extractable Ca and Mg for the Hutton and Oakleaf soil forms

Variable	**Hutton**		**Oakleaf**	
	F-ratio			
	Lime	**Year x Lime**	**Lime**	**Year x Lime**
Soil BC (cmol$_c$ kg soil^{-1})	44.74^{***}	3.33^{**}	2.82^{***}	1.10ns
Acid production load (kmol (H$^+$) ha^{-1} year^{-1})	4.65ns	-	4.33*	-
Acidification rate (pH unit year^{-1})	5.90^{*}	-	9.66**	-
Extractable Ca (cmol$_c$ kg soil^{-1})	129.41***	0.191ns	60.81***	0.099ns
Extractable Mg (cmol$_c$ kg soil^{-1})	130.63***	0.113ns	48.63***	3.74***

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

A reduction in mean soil BC values of 0.232 and 0.263 cmol$_c$ kg soil^{-1} pH unit^{-1} in the 5 and 10 tonnes lime ha^{-1} treatments, respectively, compared to the unlimed plots was recorded over the 6-year period (Table 3.2). Furthermore, a highly significant ($P<0.001$) interaction between lime application and time on soil BC was found in the Hutton soil (Table 3.1). Table 3.2 shows that soil BC was significantly ($P<0.001$) reduced within the first year of lime application, although no significant difference was found in soil BC between the 5 and 10 tonnes lime ha^{-1} treatments. A significant reduction ($P<0.001$) of 0.045, 0.343 and 0.435 cmol$_c$ kg soil^{-1} pH unit^{-1} in the 0, 5 and 10 tonnes lime ha^{-1} treatments, respectively, over the 6 years of the trial period was recorded in the Hutton soil.

Table 3.2 Soil BC values (cmol$_c$ kg soil^{-1} pH unit^{-1}) as influenced by time and lime application for the Hutton and Oakleaf soil forms

Year	**Lime application** (tonnes ha^{-1})					
	Hutton			**Oakleaf**		
	0	**5**	**10**	**0**	**5**	**10**
1998	1.144**a**[1]	1.037**c**	1.091**bc**	-	-	-
1999	1.130**ab**	0.936**e**	0.917**e**	3.269**a**[1]	3.055**a**	3.234**a**
2000	-	-	-	-	-	-
2001	1.006**d**	0.863**f**	0.821**f**	3.027**ab**	2.428**c**	2.792**bc**
2002	1.082**bc**	0.768**g**	0.660**h**	3.124**ab**	2.841**abc**	2.881**abc**
2003	1.099**b**	0.694**h**	0.656**h**	3.250**a**	2.473**c**	2.557**c**
Mean	1.092**a**[2]	0.860**b**	0.829**b**	3.168**a**[2]	2.699**b**	2.866**ab**

1 LSD 0.05 (level x time) = 0.087, column and row values having the same symbols are not statistically different at the 5% level (P<0.05)

2 LSD 0.05 (level) = 0.061, row values having the same symbols are not statistically different at the 5% level P<0.05)

1 LSD 0.05 (level x time) = 0.462, column and row values having the same symbols are not statistically different at the 5% level (P<0.05)

2 LSD 0.05 (level) = 0.326, row values having the same symbols are not statistically different at the 5% level (P<0.05)

Oakleaf soil form: Similar to the Hutton soil form, liming resulted in a highly significant (P0<001) reduction in mean soil BC over the 5-year period as shown in Table 3.1. The application of 5 tonnes lime ha^{-1} decreased mean soil BC values by 0.469 cmol$_c$ kg soil^{-1} pH unit^{-1}. Although no significant difference in soil BC between 0 and 10 tonnes lime ha^{-1} was recorded, the mean soil BC in the highest lime treatment was 0.302 cmol$_c$ kg soil^{-1} pH unit^{-1} lower than the control (Table 3.2).

Although no statistically significant interaction between lime and years on soil BC was found, there was a tendency for a decline in soil BC over time (Table 3.2). The 5 and 10 tonnes lime ha^{-1} treatments showed a reduction in soil BC of 0.582 and 0.677 cmol$_c$ kg soil^{-1} pH unit^{-1}, respectively, from 1999 to 2003.

Comparison of the experimental soils: It is clear from the results that the two experimental soils reacted differently to lime application in terms of the soil BC values. The soil BC determines to a great extent soil acidification as measured by a decrease in soil pH. Various soil constituents such as organic matter, Fe and Al oxides, and $CaCO_3$ (in calcareous soil) contribute to the soil BC at different pH values (Bolan & Hedley, 2003). Although this aspect will be dealt with in detail in another article, it is important to note that significant positive relationships between soil BC and organic C were established in both the Hutton (P<0.05) and Oakleaf (P<0.01) soils (Table 3.3).

Table 3.3 Pearson's coefficient of correlation (r) between soil BC, organic C and extractable acidity for the Hutton and Oakleaf soil forms

Variables	Hutton			Oakleaf		
	r	P	Number of observations	r	P	Number of observations
Soil BC vs organic C	+0.464	<0.05	28	+0.666	<0.01	22
Soil BC vs extractable acidity	+0.564	<0.01	28	-0.209	ns	22
Soil BC vs extractable Al	+0.571	<0.01	28	-0.214	ns	22
Soil BC vs APL	-0.520	ns	6	-0.825	<0.01	6

ns = not significant

Table 3.3 furthermore, shows that a strong positive relationship exists between soil BC and extractable acidity (P<0.01) and Al (P<0.01) in the Hutton soil, while no relationships between these parameters could be established for the Oakleaf soil. It is postulated that the significant reduction in soil BC in the Hutton soil over time and with liming (Tables 3.2 and 3.3) is mostly the result of a reduction in extractable acidity and Al due to lime application.

3.3.2 Acid production loads

Hutton soil form: In calculating APLs using Equation 3.3, no statistically significant effect of lime on APL was recorded (Tables 3.1 and 3.4). However, the net APL for the 5 and 10 tonnes lime ha^{-1} treatments was respectively 0.83 and 0.76 kmol (H^{+}) ha^{-1} year^{-1} higher than the 0 tonnes lime ha^{-1} application.

Table 3.4 Acid production loads and acidification rates for the topsoil (0-250 mm) over a six and five year period, respectively in the Hutton and Oakleaf soil forms as a function of liming

Lime rate (tonnes ha^{-1})	Initial pH (H_2O)		Acid production load (kmol (H+) ha^{-1} year^{-1})		Acidification rate (pH (H_2O) units year^{-1})	
	Hutton	Oakleaf	Hutton	Oakleaf	Hutton	Oakleaf
0	5.33	4.54	1.61**a**^{1}	4.59**a**	-0.046**a**^{1}	-0.044**a**
5	6.31	4.86	2.44**a**	8.04**ab**	-0.116**b**	-0.078**a**
10	6.47	5.15	2.37**a**	8.82**b**	-0.140**c**	-0.110**b**
LSD$_{(0.05)}$	-	-	0.87ns	3.48*	0.020*	0.035*

1 Column values having the same symbols are not statistically different at P<0.05*

2 ns = not significant

Oakleaf soil form: A statistically significant (P<0.05) increase in APL with lime application was recorded (Table 3.1), with increased acid production values of 3.45 and 4.23 kmol (H^+) ha^{-1} $year^{-1}$ between the unlimed and the 5 and 10 tonnes lime ha^{-1} treatments, respectively (Table 3.4).

Comparison between experimental soils: The APLs for all treatments in the Hutton and the Oakleaf soils control were lower than the net rates of 3 to 5 kmol (H^+) ha^{-1} $year^{-1}$ reported by Helyar *et al.* (1990). However, the APLs recorded in the 5 and 10 tonnes lime ha^{-1} treatments in the Oakleaf soil, were much higher although the crop production system was similar to that of the Hutton soil.

3.3.3 Soil BC vs soil acidification rate

Hutton soil form: The soil BC is needed as a measure of soil acidification rates as calculated from Equation 3.4. Although the soil BC for a given soil is not constant over the whole pH range (Bache, 1988), numerous studies used a constant value for soil BC in estimating acidification rates (Singh *et al*., 2003; Noble *et al*., 2002; Hill, 2003; Helyar *et al*., 1990). Non-linear regression analysis was used to identify critical pH values where a change in soil BC could be expected. Figure 3.1 (a, c & e) shows that minimum buffering (maximum slope of pH versus added OH^-) occurs between 5.51 to 7.44, 5.54 to 7.47 and 5.51 to 7.54 in the 0, 5 and 10 tonnes lime ha^{-1} treatments, respectively**.**

In order to evaluate the potential of soil BC in estimating soil acidification rates, the rate of predicted soil acidification (Equation 3.4), using soil BC at different pH ranges (<5.55, 5.55-7.50,>7.50 and 4.20-8.50), was correlated with measured soil acidification rate as indicated in Figure 3.2 (a). The measured acidification rate (pH units $year^{-1}$) was calculated from the measured annual change in basic cations, and the relationship between pH and extractable basic cations as described in Equation 3.6.

All four calculated acidification rates correlated highly significantly ($P<0.001$) with measured soil acidification rates (Figure 3.2 (a)). The ability of the four soil BCs to predict soil acidification rates is arranged as follows according to correlation with measured acidification rates: $BC_{(<5.55)}>BC_{(4.2-8.5)}=BC_{(>7.50)}>BC_{(5.55-7.50)}$. The soil acidification rate determined with the soil $BC_{(4.2-8.5)}$ crossed the 1:1 line at 0.03 pH units $year^{-1}$. Below this value the soil $BC_{(4.2-8.5)}$ slightly overestimated acidification rates and above 0.03 acidification rates were slightly underestimated. The soil $BC_{(4.2-8.5)}$ gave a regression line nearly parallel to the 1:1 line, and is therefore the most appropriate of all the soil BCs for direct prediction of soil acidification rates.

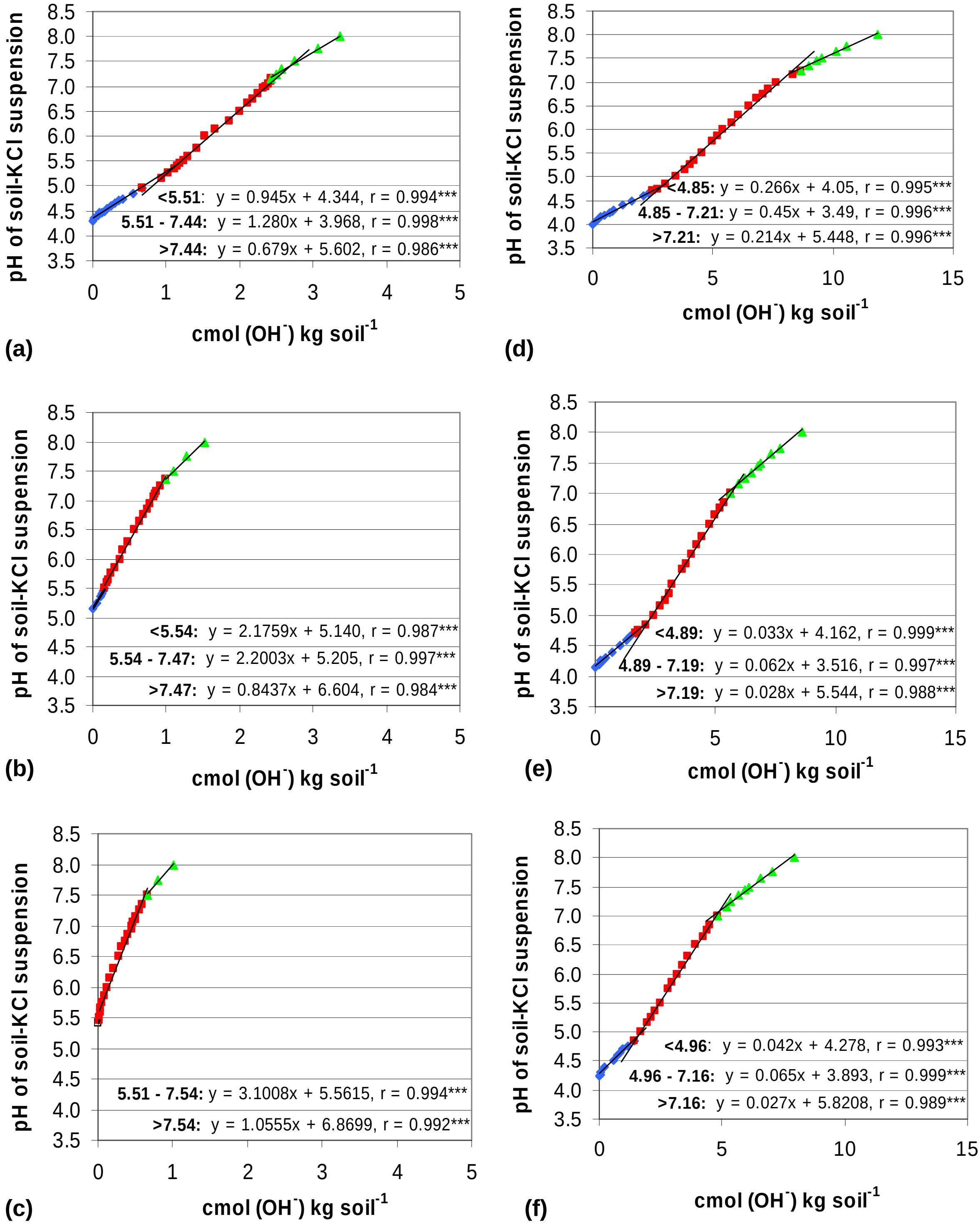


Figure 3.1 Titration curves for the critical pH ranges for (a) 0 (b) 5 and (c) 10 tonnes lime ha^{-1} treatments in the Hutton and for (d) 0 (e) 5 and (f) 10 tonnes lime ha^{-1} treatments in the Oakleaf soil forms, respectively (*** $P < 0.001$, ** $P < 0.01$ and * $P < 0.05$).

The $BC_{(<5.55)}$ crossed the 1:1 line at an acidification rate of 0.07 pH unit $year^{-1}$. Above this value, soil acidification rates were overestimated. The $BC_{(>7.5)}$ consistently underestimated soil acidification rate and $BC_{(5.55-7.50)}$ overestimated soil acidification rate (Figure 3.2 (a)).

Oakleaf soil form: The Oakleaf soil revealed good buffering to base (OH^-) addition (Figure 3.1 (d, e & f). The Oakleaf soil was moderately buffered in the mid-range (≈ 4.90 to 7.19) with increased buffering below 4.85 to 4.96, and above 7.21 to 7.16. The ability of the different soil BCs to predict soil acidification rates is as follows: $BC_{(4.2-8.5)}$ $>BC_{(5.55-7.5)}=BC_{(>7.5)}>BC_{(<5.55)}$. The soil acidification rates determined with soil $BC_{(4.2-8.5)}$ crossed the 1:1 line at a measured soil acidification rate of 0.12 pH unit $year^{-1}$. Above ,this rate soil acidification rates were overestimated and below this value an under-prediction of soil acidification occurred. The $BC_{(4.2-8.5)}$ set of values gave a regression line in closest agreement to the 1:1 line. The other soil BC ranges gave either a consistent over- or under-prediction of measured soil acidification rates (Figure 3.2 (b)).

Comparison between soil forms: Figure 3.3 (a, b) shows that linear regression analysis of the titration curves over pH range 4.2 to 8.5 shows a strong relationship ($P<0.001$) between the amount of OH^- added and pH in all lime treatments, while r values ranged from 0.983 to 0.996 for the Hutton and 0.993 to 0.996 for the Oakleaf soil form (Figure 3.3 (a, b)).

Even the 0 lime ha^{-1} treatment in the Oakleaf soil with the lowest pH of 4 gave a strong fit to the linear equation with an r^2 of 0.991. Furthermore, it has been shown that the soil $BC_{(4.2-8.5)}$ appropriately predicts measured soil acidification rates in both soils. Therefore, the soil BC over the pH range 4.2 to 8.5 was used to estimate soil acidification rates in this study.

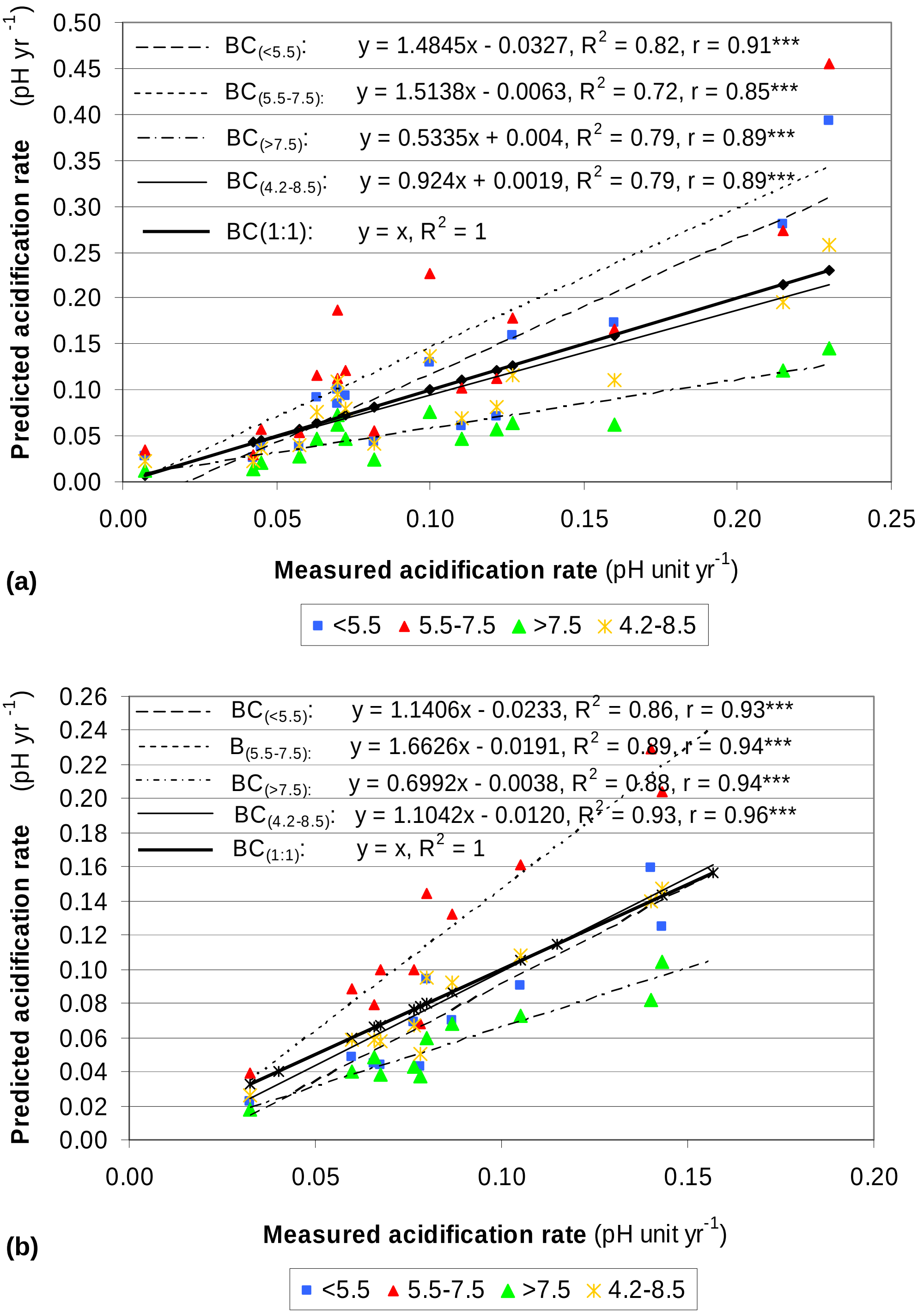


Figure 3.2 Relationship between measured and predicted acidification rates for the (a) Hutton and (b) Oakleaf soil forms (*** $P < 0.001$, ** $P < 0.01$).

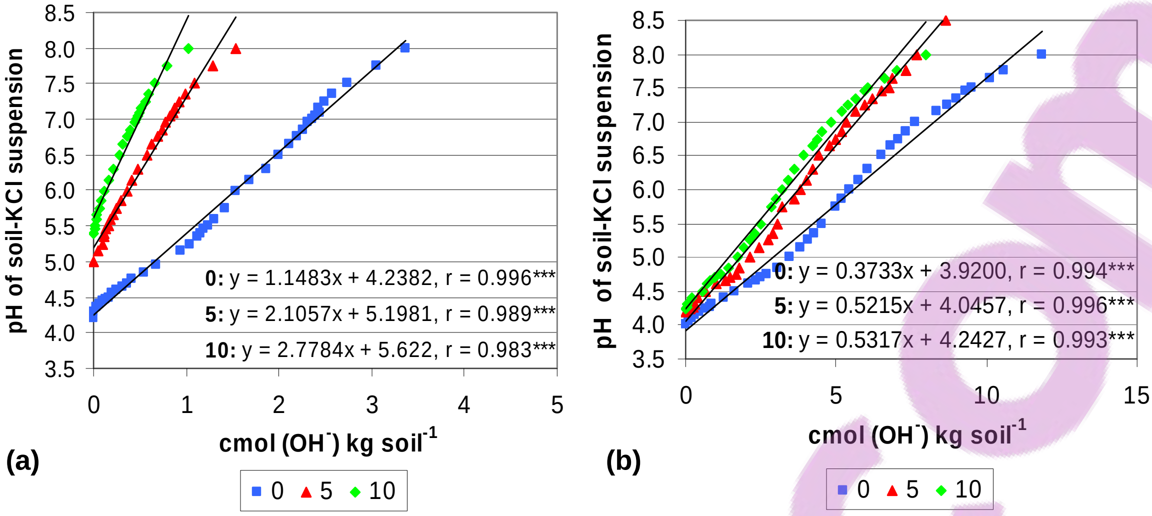


Figure 3.3 Combined titration curves for the 0, 5 and 10 tonnes lime ha^{-1} treatments in the (a) Hutton and (b) Oakleaf soils.

3.3.4 Effect of lime application on soil acidification rate

Hutton soil form: Soil acidification rates showed significant acceleration with lime application (Table 3.1). Lime addition significantly ($P<0.01$) increased the acidification rate from -0.046 to -0.116 and -0.140 pH units year^{-1} starting at initial pH (H_2O) values of 5.33, 6.31 and 6.47, respectively. Table 3.4 shows that liming resulted in a significant decrease in soil BC, consequently leading to accelerated acidification rates. Statistically significant differences in acidification rates were furthermore observed between the 5 and 10 tonnes lime ha^{-1} treatments. A significant ($P<0.05$) correlation existed between acidification rate and initial soil pH (H_2O) (Figure 3.4 (a)).

Figure 3.4 (a) shows that at an initial pH (H_2O) of 4.40, an acidification rate of 0 is predicted, and at a pH (H_2O) of between 5.5 and 6.0 an acidification rate of between -0.10 and -0.13 pH unit year^{-1} is predicted.

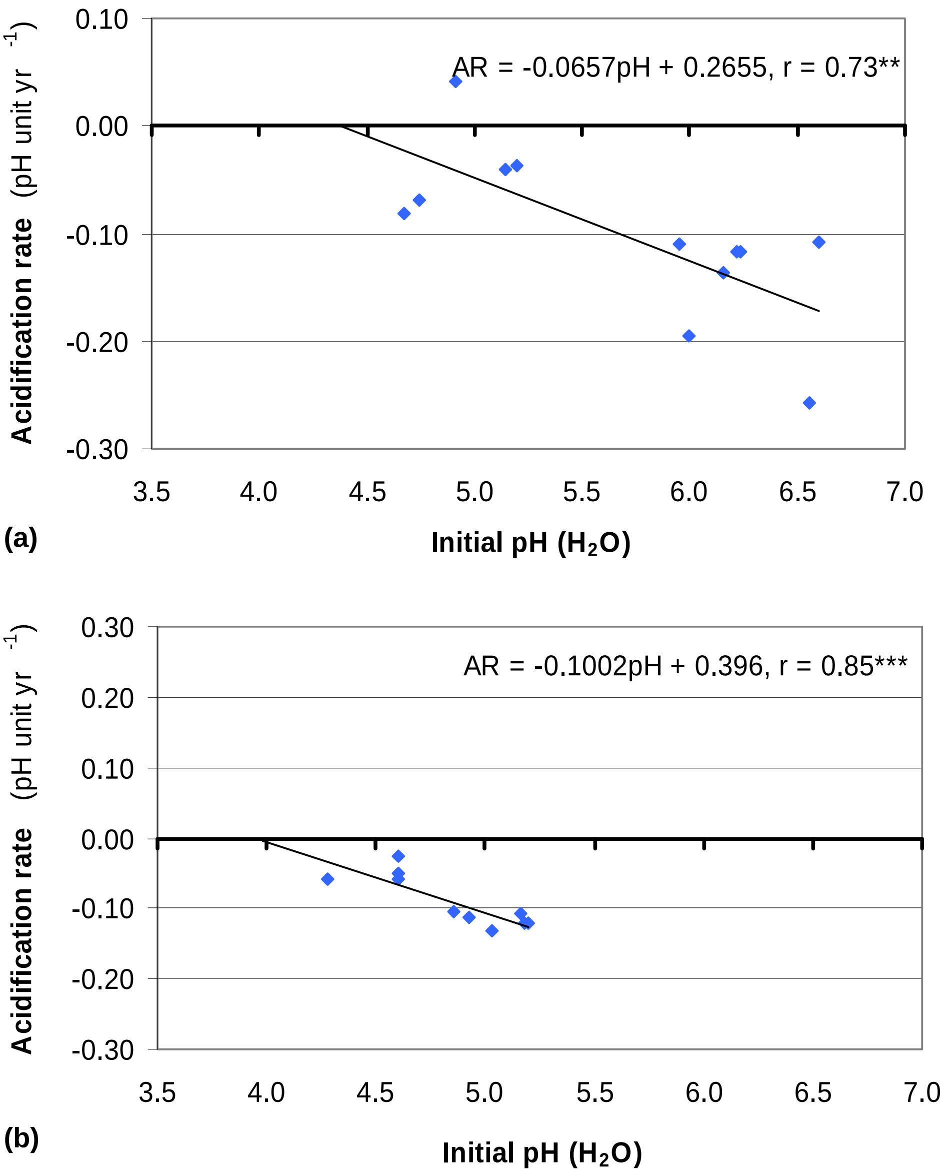


Figure 3.4 Relationship between initial pH (H_2O) and acidification rate (pH unit year^{-1}) in the (a) Hutton and (b) Oakleaf soil forms (*** P < 0.001, ** P < 0.01 and * P < 0.05).

Oakleaf soil form: Liming had a highly statistically significant (P<0.01) effect on acidification rate (Tables 3.1 and 3.4), with accelerated acidification rates with lime application recorded. Table 3.4 shows that acidification rate indicated a 0.044, 0.078 and 0.110 reduction in pH annually starting at an initial pH (H_2O) of 4.54, 4.86 and 5.15 in the 0, 5 and 10 lime ha^{-1} treatments, respectively.

Figure 3.4 (b) shows the acidification rate plotted against initial soil pH (H_2O). A significant (P<0.001) regression relationship exists between acidification rate and initial soil pH (H_2O), with an acceleration in acidification with higher initial soil pH (H_2O) values. From this relationship it is shown that at a pH (H_2O) of 3.95 an acidification rate of zero could be expected and at pH (H_2O)

of 5, -0.11 pH unit year^{-1}. The increased rate of acidification with increase in soil pH, as brought about by lime application, corresponds with the findings of Scott *et al.* (1999), Gasser (1973) and Hoyt and Henning (1982) who found an increased rate of pH decline with lime application. Scott *et al.* (1999) demonstrated acidification rates that varied from -0.02 pH unit year^{-1}, following the application of 0.5 tonnes lime ha^{-1}, to -0.10 pH unit year^{-1} after a 5 tonnes lime ha^{-1}application.

3.3.5 Lime loss and maintenance lime rate

Hutton soil form: Liming highly significantly ($P<0.001$) increased the mean amount of extractable Ca and Mg (Tables 3.1 and 3.5). Mean extractable Ca increased from 0.71, to 1.56 and 2.10 cmol$_c$ kg^{-1}, in the 0, 5 and 10 tonnes lime ha^{-1} treatments, respectively. Table 3.5 shows an increase in extractable Mg of 0.61 and 1.01 cmol$_c$ kg^{-1} compared to the unlimed treatment.

Table 3.1 shows that no significant interaction was found between lime level and time. After lime application in 1997, maximum extractable Ca and Mg levels were obtained two to three years after lime application (Table 3.5). However, no significant decrease or increase in extractable Ca and Mg was recorded over 6 years, and significantly higher extractable Ca and Mg values were observed in the limed compared to the unlimed plots at the end of 2003. In 2003, no statistically significant differences in Mg values were found between the recommended 5 tonnes ha^{-1} application rate and 10 tonnes lime ha^{-1}. A statistically significant ($P<0.05$) linear decrease in the sum of extractable Ca + Mg with time (Figure 3.5 (a)) was shown after maximum extractable Ca + Mg was reached.

Table 3.5 Extractable Ca and Mg values (cmol$_c$ kg soil^{-1}) as influenced by time and lime application for the Hutton and Oakleaf soil forms

Year	**Lime application** (tonnes ha^{-1})											
	Hutton						**Oakleaf**					
	Ca			**Mg**			**Ca**			**Mg**		
	0	**5**	**10**	**0**	**5**	**10**	**0**	**5**	**10**	**0**	**5**	**10**
1998	0.70**a**	1.40**b**	1.67**bc**	0.56**a**	1.03**b**	1.32**cd**						
1999	0.76**a**	1.76**bc**	2.07**de**	0.59**a**	1.38**cd**	1.60**d**	0.23**a**	0.98**de**	1.83**f**	0.10**a**	0.58**b**	1.13**c**
2000	0.87**a**	1.49**b**	2.54**f**	0.62**a**	1.10**bc**	1.90**e**	0.34**a**	0.89**cde**	1.23**de**	0.14**a**	0.74**b**	0.60**b**
2001	0.66**a**	1.57**b**	2.35**ef**	0.53**a**	1.25**b**	1.80**de**	0.38**a**	0.84**b**	1.29**e**	0.26**a**	0.58**b**	0.84**b**
2002	0.63**a**	1.56**bc**	1.98**cde**	0.44**a**	1.05**b**	1.38**cd**	0.20**a**	0.45**ab**	1.22**de**	0.22**a**	0.22**a**	0.64**b**
2003	0.66**a**	1.60**b**	1.97**cde**	0.44**a**	1.05**b**	1.26**b**	0.46**a**	0.50**ab**	1.18**de**	0.20**a**	0.25**a**	0.59**b**
Mean[2]	0.71**a**	1.56**b**	2.10**c**	0.53**a**	1.14**b**	1.54**c**	0.32**a**	0.73**b**	1.35**c**	0.18**a**	0.47**b**	0.77**c**

[1] LSD 0.05 (level x time) = 0.42 (Ca) and 0.28 (Mg); column and row values having the same symbols are not statistically different (P<0.05).

[2] LSD 0.05 (level) = 0.17 (Ca) and 0.13 (Mg); row values having the same symbols are not statistically different (P<0.05)

[1] LSD 0.05 (level x time) = 0.42 (Ca) and 0.26 (Mg); column and row values having the same symbols are not statistically different (P<0.05)

[2] LSD 0.05 (level) = 0.19 (Ca) and 0.12 (Mg); row values having the same symbols are not statistically different (P<0.05)

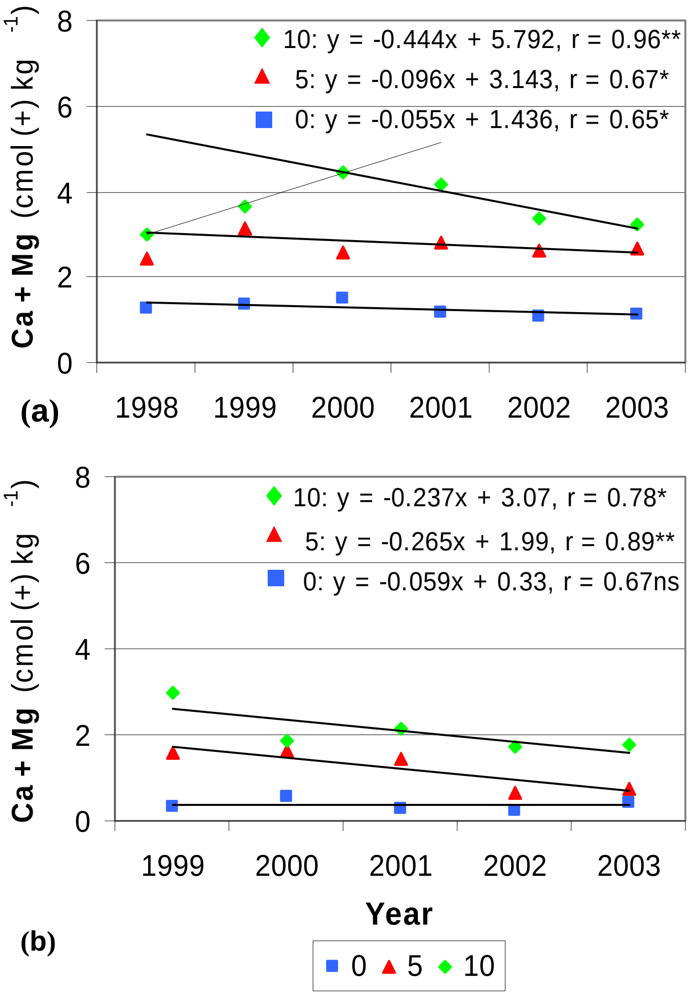


Figure 3.5 The relationships between extractable (Ca + Mg), and time in the (a) Hutton and (b) Oakleaf soil forms.

This can be attributed to natural acidification processes, leaching losses, as well as crop uptake and consequent removal of Ca and Mg through the harvesting of the seed. After obtaining maximum concentrations in 1999 and 2000 in the 5 and 10 tonnes ha^{-1} lime rates, respectively, the amount of extractable Ca + Mg varied linearly with time (Figure 3.5). The slopes of the regression lines increased with the rate of lime application, with values of -0.055, -0.096 and -0.444 cmol$_c$ kg^{-1} for the 0, 5 and 10 tonnes lime ha^{-1} application, respectively (Figure 3.5 (a)). This indicates that the annual loss (leaching and removal by crop) in basic cations increased with lime application.

The annual maintenance lime requirement, calculated from Equation 3.7, amounted to 0.2, 0.3 and 1.4 tonnes $CaCO_3$ ha^{-1} year^{-1} for the 0, 5 and 10 tonnes lime rates in the Hutton soil form, respectively (Table 3.6).

Table 3.6 Maintenance lime requirement rates in the topsoil (0-250 mm) of the Hutton and Oakleaf experimental soils as a function of liming

Lime rate (tonnes lime ha^{-1})	**Maintenance lime requirement** (tonnes $CaCO_3$ ha^{-1} year^{-1})	
	Hutton	**Oakleaf**
0	0.2	0
5	0.3	0.8
10	1.4	0.8

The fairly rapid loss of lime from the 10 tonnes lime ha^{-1} treatment was probably not only caused by cultivation and increased mineralization rates of organic matter, but also by the high lime application level. It can be postulated that free lime was present in the soil for the 10 tonnes ha^{-1} lime treatment and was leached, although this phenomenon was not determined. Gasser (1973) postulated that the loss of lime doubles for each increase of one pH unit. Hoyt and Henning (1982) speculated that if the soils they were studying would have been limed to pH 5.7 instead of 6.7, the loss of lime might have been one-half of that found in the experiment (0.49 tonnes $CaCO_3$ ha^{-1} year^{-1}).

Oakleaf soil form: Liming significantly ($P<0.05$) increased the mean extractable Ca by 0.41 and 1.03 cmol$_c$ kg^{-1}, and the Mg by 0.29 and 0.59 cmol$_c$ kg^{-1} in the 5 and 10 tonnes lime ha^{-1} treatments, respectively (Table 3.5). Although no significant interaction between lime level and time was recorded for extractable Ca, a highly significant interaction was found for extractable Mg (Table 3.1). The extractable Ca and Mg in the unlimed plot remained relatively unchanged over 5 years, while a decreasing trend in extractable Ca was recorded in the limed treatments. A highly significant ($P<0.001$) decrease in extractable Mg was found within 4 and 2 seasons in the 5 and 10 tonnes lime ha^{-1} plots, respectively (Table 3.5). Factors (e.g. leaching due to rainfall, yield removal) responsible for reacidification caused a decrease in the extractable Ca and Mg in the 5 tonnes lime ha^{-1} rate to such an extent that no significant difference could be found compared to the control after four years.

Figure 3.5 (b) shows that extractable Ca and Mg varied linearly with time with statistically significant ($P<0.05$ and $P<0.01$) decreases in extractable Ca and Mg over the trial period in the 5 and 10 tonnes lime ha^{-1} treatments, respectively. Although a slight decrease in the amount of Ca^{2+} and Mg^{2+} was observed in the control, the relationship was not statistically significant as shown in Figure 3.5 (b).

The maintenance lime requirement for the Oakleaf soil ranged from 0 tonnes in the control, to 0.8 tonnes $CaCO_3^{-1}$ ha^{-1} year^{-1} in the 5 and 10 tonnes lime ha^{-1} treatments (Table 3.6). Although liming increased the rate of lime loss between unlimed and limed plots, no apparent difference in maintenance lime requirement was found between the 5 and 10 tonnes ha^{-1} lime rates.

Comparison between experimental soils: According to the FSSA (2003), maintenance applications of agricultural lime of 0.3 to as much as 1.5 tonnes $CaCO_3$ ha^{-1} year^{-1} are necessary under normal maize cultivation practices in South Africa. Although the average maintenance lime requirement for the 10 tonnes ha^{-1} lime treatment of the Hutton soil and the lime treatments of the Oakleaf soil are in accordance with lime losses generally expected, the acidification rates were in general moderate for the two experimental soils. This can be ascribed to the conservative (low risk) fertilizer application strategies that were evaluated for resource-poor farmers. Another reason for the low acidification rates is the use of limestone ammonium nitrate (LAN (28% N)) as nitrogen (N)-source. LAN is ranked as an N-source with a low acidifying effect due to its nitrate and lime content. Nitrogen-containing fertilizers which contain large quantities of ammonium and amine nitrogen have a greater acidifying effect on soil than nitrate-containing fertilizers (FSSA, 1998).

3.4 CONCLUSIONS

Results from the study showed that acidification rates increased with lime application, but due to stronger soil BC in the Oakleaf soil reacidification was found to be lower. Continuous maize cultivation and inappropriate nitrogenous fertilization have the potential to generate sufficient acidity that crop production (e.g. maize, legumes etc.) could be abandoned due to Al and manganese toxicity in many agricultural lands in Mlondozi. It is furthermore important that soils should be regularly tested and should be limed to a point where phytotoxic levels of extractable Al are eliminated. Management strategies (e.g. split application of N) to reduce the acidifying effect of fertilizer should also be implemented. However, the assessment of acidification rates could be a valuable tool in determining soil acidification and serve as an indicator to adapt management practices to reduce soil acidification. This stresses the importance of implementing sound management strategies in conjunction with government interventions, especially for resource-poor farmers.

4

LIMING EFFECTS OF SOIL PROPERTIES, NUTRIENT AVAILABILITY AND GROWTH OF MAIZE

4.1 INTRODUCTION

A generation ago, prevention of starvation due to food shortage on a global scale was the primary goal in agricultural strategies, a concern successfully addressed by the so-called “green revolution” in various aspects. However, there has been a concomitant rise in incidence of nutrient deficiencies in human populations worldwide (Graham & Welch, 2000). In South Africa, resource-poor rural communities are especially vulnerable because most of the household’s food is produced on the land on which they live. If nutrient deficiencies or toxicities occur in these soils, their quality of life can be influenced dramatically (Steyn & Herselman, 2006). Furthermore, many of the resource-poor rural areas are characterized by acid soils, commonly deficient in P, Ca, Mg, Mo and Si, with Al and Mn at toxicity levels. Aluminium toxicity limits nutrient use efficiency and crop production due to reduced root growth which greatly restricts the ability of the plant to explore the soil volume for nutrients and water.

Liming of acid soils to alleviate soil acidity is a common practice, changing the availability and soil solution concentrations of various nutrients. Increasing pH, HCO_3^- or Ca^{2+} concentration of the soil solution may interact with solubility and uptake of elements, and sometimes change the general vitality or growth rate of plants (Tyler & Olsson, 2001). Several studies have shown that the solubility of P, Ca, Mg, Mo and Si increases with increasing pH while the solubility and availability of Zn, Cu, B, Mn, Fe and Al in soils declines with increasing pH (Mengel & Kirkby, 1987; Reddy *et al.*, 1995; Haynes, 2001; Thibaud & Farina, 2006). Furthermore, economic considerations often require judicious management of applied fertilizer inputs under resource-poor farming conditions. Ohki (1983) showed that soils with pH (H_2O) of less than 5.0 often contain toxic levels of Mn that may be detrimental to growth of maize.

The present study was undertaken to investigate the relationships between nutrient availability and maize grain yield in a resource-poor farming area in the Mpumalanga Province of South Africa. This area is characterized by acid soils deficient in Ca, Mg, P and K (Booyens *et al.*, 2000). Steyn and Herselman (2006) further reported that trace elements such as B, Co, Cu, Fe, I, Mn, Mo, Se and Zn have a high risk of being deficient in this area. The objectives of the study were to determine (i) the effect of lime application on soil and leaf nutrient concentrations, and (ii) critical nutrient levels in soil and maize leaves as affected by soil acidity and lime application.

4.2 MATERIAL AND METHODS

4.2.1 Experimental layout and procedure

The experimental layout and procedure described in Chapter 2 are applicable in this discussion as the data derived from the two field trials were used to evaluate the objectives as stated. Some additional chemical topsoil (0-250 mm) characteristics of the experimental soils that were not mentioned in Table 2.1 are summarized in Table 4.1.

Table 4.1 Selected soil chemical topsoil (0-250 mm) properties[1] of the experimental sites

	Experimental soil	
Soil form[2]	Hutton	Oakleaf
P (mg kg^{-1})	5.59	9.32
K (mg kg^{-1})	81	38
Ca (mg kg^{-1})	150	90
Mg (mg kg^{-1})	57	43
Cu (mg kg^{-1})	2.78	1.61
Zn (mg kg^{-1})	0.53	0.89
B (mg kg^{-1})	0.81	3.81
Mo (mg kg^{-1})	0.01	0.01

1 According to the The Non-Affilliated Soil Analysis Work Committee (1990)

2 Soil classification working group, 1991

4.2.2 Soil and leaf sampling and analysis

Topsoil samples (0-250 mm) were taken annually in February/March at flowering. Eight soil samples were taken within each plot between the rows and a composite sample was made up. The composite samples were air-dried and ground to pass through a 2 mm sieve. Soil pH (H_2O) was determined in a 1:2.5 (soil:water) suspension (Reeuwijk, 200). Extractable acidity was determined with a 1 mol dm^{-3} KCl extraction. Extractable P was determined according to the Bray-1 extraction method. The P concentrations of the extracts were determined on a continuous flow analyzer (Bray & Kurtz, 1945). The NH_4OAc (1 mol dm^{-3}, pH 7) method was used to determine the extractable cations Ca, Mg and K. The cations in solution were determined on an atomic absorption spectrophotometer (Thomas, 1982). The di-ammonium EDTA method was used to determine Cu, Zn, Co and Mo. Water-soluble B was determined by the hot water extraction method. Copper, Zn, Mo, Co and B were determined by ICP-MS (The Non-Affiliated Soil Analysis Work Committee, 1990).

Maize leaf samples were taken annually at flowering (end of February or beginning of March), 8 to 10 weeks after planting. The maize leaf immediately opposite and below the first ear was sampled. The leaf samples were washed in deionized water, dried at 70 ºC to constant mass and milled. Nitrogen was determined by dry oxidation (Bellomonte *et al.*, 1987) using a Carlo-Erba CNS instrument. For the determination of P, K, Ca, Mg, K, Fe, Mn, Al, Cu, Zn and B, 1 g samples were wet-digested on a digestive block with 1:3 (nitric acid (HNO_3 (c)) : perchloric acid ($HClO_4$ (c)) and determined by ICP-OES (Zasoski & Burau, 1977). For the determination of Mo, 0.5 g leaf samples were wet-digested with HNO_3 (c) and determined by ICP-MS (Chao-Yong & Schulte, 1985).

4.2.3 Statistical analysis and data interpretation

The effects of liming on soil fertility properties, leaf nutrient concentrations and maize grain yield were evaluated statistically by analysis of variance (ANOVA) (GenStat, 2003). The values that will be discussed are annual replicate means per lime application level and replicated means per lime application level over years. The Bonferroni multiple comparison test for means separation was used to test all the main effects at a 5% probability level.

The evaluation of critical threshold values for soil and leaf nutrients 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.* (2004, 2008), but the conclusion was that applying relative yield to field data enables one to include results from different climatic zones, soil types, maize cultivars, plant spacing and seasons. Relative yields were determined as percentages of the highest yield annually in each of the three randomized blocks and the average of these replicates presented the relative yield for each treatment. Critical threshold nutrient levels, where a significant decrease in relative yield could be expected, were determined by three methods namely: (i) Non-linear regression analysis using the “broken stick model” (GenStat, 2003) to obtain the upper threshold value and biological optimum. (ii) The probability approach of Cate and Nelson (1971) to obtain the lower threshold value (Van Biljon *et al.*, 2008). The “between groups” sum of squares is calculated directly by procedures commonly used in analysis of variance of one-way classification data (Cate & Nelson, 1971; Möhr, 1976; GenStat, 2003). (iii) At a 90% relative yield, where a 10% reduction in growth was recorded. The relationships between relative yield and nutrient concentrations were based on pooled data for both experimental sites.

4.3 RESULTS AND DISCUSSION

4.3.1 Effect of liming on soil and leaf nutrient values

Variance analyses of the soil and leaf nutrient content as affected by lime application are given in Tables 4.2 to 4.4.

Table 4.2 ANOVA table of probabilities of lime treatment effects on soil and leaf nutrients in the Hutton and Oakleaf soil forms

Variable	Hutton		Oakleaf	
	F-ratio			
	Soil	Leaf	Soil	Leaf
N	-	6.26**	-	1.06ns
P	3.42**	7.00**	0.48 ns	0.19 ns
K	0.64ns	0.19ns	1.54 ns	0.42 ns
Ca	155.38***	57.33***	22.09***	12.40***
Mg	160.63***	79.21***	35.47***	57.91***
Cu	15.25***	0.49ns	1.68 ns	0.96 ns
Zn	5.41**	4.03*	0.62 ns	7.09**
B	14.92***	1.25ns	15.90***	1.62 ns
Mo	2.99*	-	3.80*	-
Mn	-	9.07***	-	6.99**
Fe	-	7.20**	-	1.76 ns
Al	351.28***	1.13ns	37.47***	1.21 ns
Yield	5.22**		33.09***	

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

Hutton soil form: A secondary effect of soil acidity is low soil Ca and Mg values, resulting in low leaf Ca and Mg concentrations. Liming is the most common and effective practice to replenish the soil cation pool (Fageria & Baligar, 2003). Table 4.3 shows that liming significantly increased extractable soil Ca, Mg, Cu, Zn and Mo, and decreased soil P and B levels.

A significant increase in leaf N, P, Ca and Mg, and a decrease in leaf Mn and Fe concentrations were recorded (Table 4.4).

Table 4.3 The effect of lime application on selected soil chemical properties in the Hutton and Oakleaf soil forms

Nutrient	**Lime application (tonnes ha^{-1})**					
	Hutton			**Oakleaf**		
	0	**5**	**10**	**0**	**5**	**10**
P (mg kg^{-1})	6.62**a**	4.90**b**	4.71**b**	7.54**a**	6.68**a**	7.25**a**
K (mg kg^{-1})	77.2**a**	78.9**a**	71.4**a**	35.5 **a**	30.9 **a**	34.4**a**
Ca (mg kg^{-1})	142.7**a**	312.4**b**	419.1**c**	96**a**	161**b**	281**c**
Mg (mg kg^{-1})	64.6**a**	139.5**b**	188.3**c**	30.6**a**	54.1**b**	99.2**c**
Cu (mg kg^{-1})	2.52**a**	2.84**b**	3.16**b**	1.33**a**	1.42**a**	1.38**a**
Zn (mg kg^{-1})	0.74**a**	0.88**b**	0.96**b**	0.810**a**	0.71**a**	0.67**a**
B (mg kg^{-1})	0.39**b**	0.42**b**	0.33**a**	1.81**a**	1.53**b**	1.60**b**
Mo (mg kg^{-1})	0.59**a**	0.69**ab**	0.71**b**	0.24**a**	0.24**ab**	0.26**b**

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

Oakleaf soil form: The application of lime had a highly significantly effect on increased soil Ca, Mg and Mo and decreased soil B levels. No effects on available soil P, K, Cu and Zn values was recorded (Tables 4.2 and 4.3). A highly significant increase in leaf Ca, Mg and Zn, and a decrease in leaf Mn, were found (Tables 4.2 and 4.4).

Table 4.4 The effect of lime application on leaf nutrient uptake as reflected by the first ear leaf at tasselling to initial silking in the Hutton and Oakleaf soil forms

Nutrient	**Lime application (tonnes ha^{-1})**					
	Hutton			**Oakleaf**		
	0	**5**	**10**	**0**	**5**	**10**
N (%)	1.65**a**	1.64**a**	1.81**b**	1.73**a**	1.76**a**	1.81**a**
P (%)	0.14**a**	0.16**ab**	0.17**b**	0.21**a**	0.21**a**	0.21**a**
K (%)	1.62**a**	1.60**a**	1.63**a**	1.23**a**	1.25**a**	1.20**a**
Ca (%)	0.29**a**	0.41**b**	0.45**b**	0.25**a**	0.30**b**	0.32**b**
Mg (%)	0.23**a**	0.32**b**	0.37**c**	0.17**a**	0.27**b**	0.35**c**
Cu (mg kg^{-1})	8.09**a**	7.9**a**	8.2**a**	8.3**a**	8.1**a**	8.7**a**
Zn (mg kg^{-1})	32.0**b**	28.9**a**	34.3**c**	24.0**a**	28.7**b**	30.4**b**
B (mg kg^{-1})	16.1**a**	16.9**a**	19.3**a**	15.3**a**	16.2**a**	13.7**a**
Mn (mg kg^{-1})	43.2**b**	36.9**a**	35.8**a**	64.6**b**	51.4**a**	55.9**a**
Fe (mg kg^{-1})	304**b**	228**b**	225**b**	322**a**	267**a**	256**a**
Al (mg kg^{-1})	526**a**	430**a**	396**a**	642**a**	476**a**	425**a**
Yield (tonnes ha^{-1})	2.25**a**	2.73**b**	2.78**b**	0.34**a**	0.79**b**	1.32**c**

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

Comparison between soils: In general, liming increased the mean extractable Ca and Mg values over 6 years to above the optimum Ca range of 300 - 2000 mg kg^{-1} and Mg >50 mg kg^{-1}, respectively, in the Hutton soil, as suggested by Buys (1986). However, liming did not increase extractable Ca values to within the optimum range in the Oakleaf soil form, but 5 and 10 tonnes lime ha^{-1} increased extractable Mg to above the critical level of 50 mg kg^{-1}. Soil P and K values were deficient in both soils (Tables 4.3 and 4.5).

Table 4.5 Critical thresholds for selected soil nutrient indices

Nutrient indices	Soil nutrient content		
	Deficiency threshold (mg kg^{-1})	Critical threshold (mg kg^{-1})	90% relative yield (mg kg^{-1})
K	<80[1]	50[4]	78-95
Ca	<200[1]	228[4], 345[5]	348
Mg	<50[1]	78[4], 105[5]	140
Cu	<1[2]	1.68[4], 2.83[5]	2.85
Zn	<3[2]	-	-
B	<1[3]	-	-

1 Buys (1986)
2 Steyn & Herselman (2006)
3 Mengel & Kirkby (1987)
4 Cate & Nelson (1971) procedure
5 Broken-stick analysis

Leaf N and P concentrations below critical concentrations were recorded in the Hutton soil, and the Oakleaf soil was deficient in leaf N and K nutrients according to values reported in Table 4.6. Because of the relatively large amounts of N used by crop plants, N is usually the nutrient element applied to agricultural land in the largest amounts. Once Al toxicity and P deficiency have been managed by a combination of soil amendments, yield potential is likely to be limited by N supply (Haynes, 2001). Due to the low leaf N concentrations recorded in the present study, increased application of N fertilizer and/or the use of legumes in rotation, as intercrops, or green manures, needs to be implemented.

Steyn and Herselman (2006) raised a concern that the trace elements B, Co, Cr, Cu, Fe, I, Mn, Mo, Se and Zn have a high risk of being deficient in Mpumalanga, especially in resource-poor farmlands. Over-liming may further cause deficiency of micronutrients such as Zn, Cu and B, if soils are relatively poor in these elements. A decrease in soil B levels with liming was observed (Tables 4.2 and 4.3) in both experimental soils. Although liming did not suppress B levels to below deficient levels in the Oakleaf soil, the hot water-soluble B in the Hutton soil was far below the deficiency (<1 mg kg) threshold suggested by Mengel and Kirkby (1987) and Steyn and

Herselman (2006). However, liming had no effect on leaf B uptake and both soils had leaf B concentrations within the adequate range of 5 to 25 mg kg^{-1}.

Table 4.6 Critical threshold values for selected plant nutrient indices in maize crops

Nutrient indices	**Plant nutrient concentration**	
	Adequate Range	**Toxicity/Excessive Threshold**
N (%)	2.60-4.00[1]	>4.0[3]
P (%)	0.17-0.32[1]	>0.8[3]
K (%)	1.50-3.50[2]	>4.0[3]
Ca (%)	0.20-0.50[3]	>0.9[3]
Mg (%)	0.20-1.00[1]	>0.85[3]
Cu (mg kg^{-1})	6-20[3]	>50[3]
Zn (mg kg^{-1})	18-60[3]	>150[3]
B (mg kg^{-1})	5-25[1]	>25[1]
Mo (mg kg^{-1})	0.1-0.5[1]	-
Fe (mg kg^{-1})	30-200[3]	>350[1]
Mn (mg kg^{-1})	20-200[3]	>300[1]
Al (mg kg^{-1})	<200[1]	>400[1]

1 Reuter and Robinson (1997)
2 Hanway (1962)
3 Weir and Cresswell (1994)

On the basis of 3 mg kg^{-1} as the threshold value for Zn deficiency, all the treatments in both soils had very low soil Zn values. Lime application did not affect Zn level in the Oakleaf soil form, but a non-significant trend of increase in Zn by 0.14 and 0.22 mg kg^{-1}, was observed with 5 and 10 tonnes lime ha^{-1}, respectively, in the Hutton soil form. Parker *et al.* (1991) reported that Zn deficiency of crops, especially maize, is very common. It was, however, found that liming did not influence the uptake of leaf Zn content in the two sites studied. Although soil Zn levels were low, both soils had leaf Zn concentrations within the adequate range of 18 to 60 mg kg^{-1}.

Soil and leaf Cu values were in the optimum range (>1 mg kg^{-1} and >6 mg kg^{-1}, respectively) in both experimental soils. The extractable soil Mo values in the Oakleaf soil were in the deficiency range with an observed increase in Mo with lime application. In some areas, however, particularly on acid soils (pH (H_2O) <5.5), Mo deficiency can arise because of Mo fixation in the soil. Mo deficiency symptoms are commonly observed on soils derived from quartzic material, as is the case in the study area (Mengel & Kirkby, 1987).

4.3.2 Critical soil nutrient concentrations and yield

Critical concentrations are not single values but a narrow range of nutrient concentrations, above which the plant is over supplied with nutrients, and below which the plant is deficient and a growth stress may be expected to occur (Melsted *et al.*, 1969). According to Ulrich and Hills (1973), the critical concentration lies within the transition zone and is associated with (i) the breaking point of the curve; (ii) the midpoint of the transition zone; or (iii) a reduction in growth, usually 10%.

The values discussed are pooled data per lime application level for both experimental soils. The regression equations presented in Figures 4.1 (a-d) describe relationships between soil concentrations of the nutrients tested and relative grain yield. Critical threshold values for soil K, Ca, Mg and Cu concentration indices, according to the Cate-Nelson method, non-linear (broken-stick) analysis and at a 90% relative yield, are given in Tables 4.5 and 4.7. No relationship could be established between yield and soil P, B, Zn or Mo, and between yield and leaf nutrient concentrations. Furthermore, critical threshold levels according to the broken-stick method could only be determined for soil Ca, Mg and Cu as indicated in Table 4.6. Figure 4.1 shows the typical relationship of increasing yields with increasing soil K, Ca, Mg, and Cu contents.

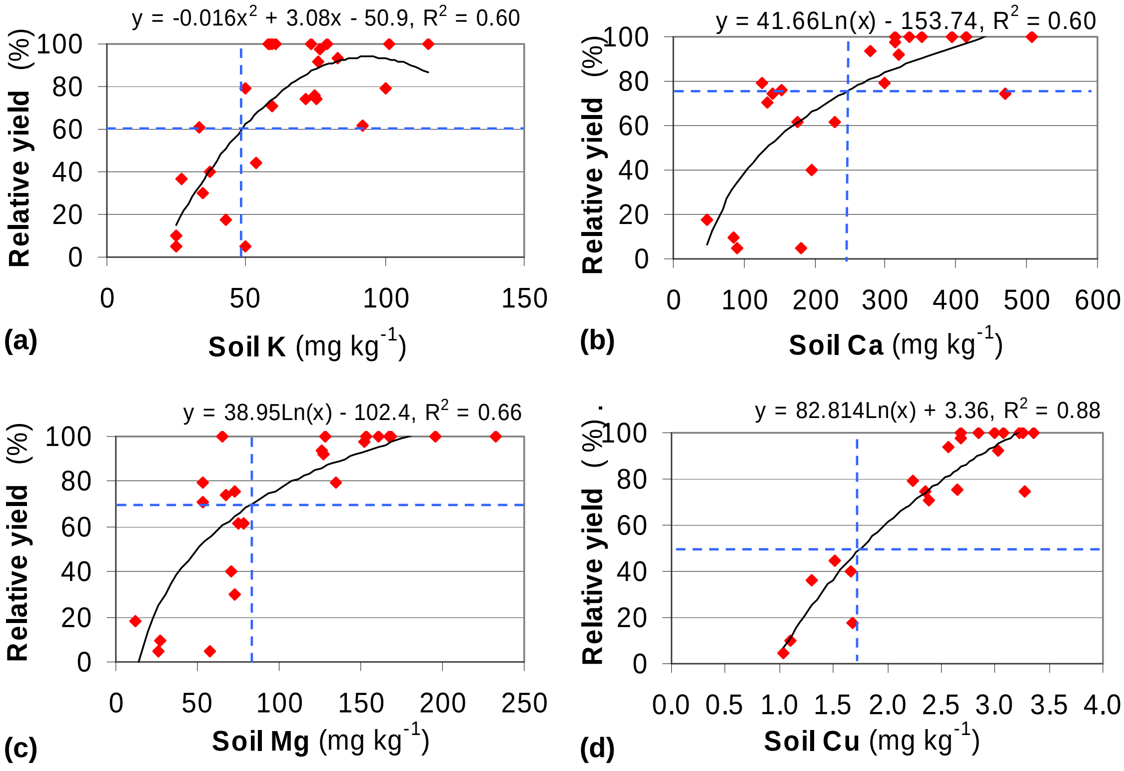


Figure 4.1 The relationship between relative yield and soil (a) K, (b) Ca, (c) Mg, and (d) Cu.

Table 4.5 and 4.6 shows that the measured critical threshold values for soil Ca, Mg and Cu were 228-345, 78-105 and 68-2.83 mg kg soil^{-1}, respectively, which are in the range of adequate values reported by Buys (1986) and Steyn and Herselman (2006). However, critical K levels (Table 4.5) were lower than the adequate range reported by Buys (1986) and Mengel and Kirkby (1987).

Table 4.7 Non-linear regression analysis between relative yield and selected soil nutrients for pooled data in the Hutton and Oakleaf soil forms

Variables	**R^2 (%)**	**F**	**Critical value** (mg kg^{-1})
Relative yield vs soil Ca	57.6	70.73*	345
Relative yield vs soil Mg	63.4	80.94*	105
Relative yield vs soil Cu	89.4	282.42*	2.83

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

4.4 CONCLUSIONS

The present study indicates that a risk exists for soil P, K, B and Zn to be deficient in the study area. However, the deficiencies of Cu, Zn and B were not reflected in plant uptake with leaf concentrations well above adequate ranges. Critical values, as reported in this study, are not infallible but can serve as a guide in the interpretation of the problems associated with soil acidity. If used properly they can help identify nutrition deficiencies and imbalances responsible for yield depression which could assist in the implementation of useful and sound cultivation practices.

5

EFFECT OF SOIL ACIDITY AMELIORATION ON MAIZE YIELD AND NUTRIENT INTERRELATIONSHIPS IN SOIL AND PLANTS USING STEPWISE REGRESSION AND NUTRIENT VECTOR ANALYSIS

5.1 INTRODUCTION

Soil acidity is as a major constraint to crop production throughout the world (Sumner & Noble, 2003). Venter *et al.* (2001) reported that although the extent of man-made topsoil acidity in South-Africa is difficult to quantify, it is estimated that 37% of the cropped area in the summer rainfall region, west of the Drakensberg, is acidified to some extent. In the winter rainfall region 60% of soil analyses indicated an acidity problem (Venter *et al.*, 2001). Furthermore, vast areas in South Africa occupied by resource poor rural communities in the higher rainfall areas are characterized by acid soils, and commonly deficient in Ca, Mg, Mo and P (Beukes, 1995). The fertility of acid soils is limited by two fundamental factors; the presence of phytotoxic substances (e.g. soluble Al and Mn) and nutrient deficiencies (e.g. P, Ca, and Mg). Aluminium toxicity limits nutrient use efficiency and crop production through reducing root growth which greatly restricts the ability of the plant to explore the soil volume for nutrients and water. This also leads to restricted uptake of P, Ca, and Mg by plant roots and deficiencies of these nutrients are common in plants suffering from Al toxicity (Foy & Fleming, 1978; Foy, 1984; Haynes, 2001).

Aluminium toxicity interferes with active ion uptake processes functioning across the root-cell plasma membrane (Wright, 1989; Haynes, 2001). Toxic concentrations of Al have been shown to reduce P and Ca uptake by crops. The mechanism of Al/P interactions is proposed to be an adsorption/precipitation reaction between Al and P at the root surface or in the root free space (McCormick & Borden, 1974; Tan & Keltjens, 1990; Haynes, 2001). Aluminium toxicity also results in inhibition of Ca and Mg uptake by plants. Mengel and Kirkby (1987) reported that Al (probably $AlOH^{2+}$) specifically depressed Mg uptake in oats whereas the uptake of Ca and K was little affected. Foy (1992), also, reported antagonistic effects between Ca and Al in soil. These effects include decreased susceptibility to Al toxicity at increased Ca levels, and reduced uptake and translocation of Ca as solution Al^{3+} is increased (Haynes, 2001). On acidic soils, excessive levels of soluble Mn can induce Fe deficiency in some plants, thereby causing the development of Mn toxicity symptoms on older leaves and Fe deficiency symptoms on younger leaves (Grundon *et al.*, 1997; Thibaud & Farina, 2006). Sometimes excessive Mn can induce deficiency of Mg, and Ca as well. In the case of Mn induced Ca deficiency ("crinkle leaf"), reported in cotton and beans, the transportation of Ca in the growing points is affected (Mengel & Kirkby, 1987).

The present study was undertaken to investigate the effect of lime application on maize yield and nutrient interrelationships in soils and plants. The study area is characterized by acidic soils that could lead to toxic levels of Al and Mn detrimental to maize growth. Although it is generally accepted that liming effectively reduces elevated concentrations of Al and Mn in soil, it could decrease the availability of B, Zn and Cu in soil (see Chapter 4). It is therefore also necessary to study nutrient interactions as affected by soil acidity in order to understand the potential soil and leaf nutrient imbalances that may arise from lime application. The objectives of the study were therefore to (i) determine the interrelationships between maize grain yield, soil and leaf nutrient contents and (ii) evaluate possible lime induced nutrient interactions by means of nutrient vector analyses.

5.2 MATERIAL AND METHODS

5.2.1 Experimental procedure

Two field trials, which were discussed in Chapter 2, were used to evaluate interrelationships between soil and leaf nutrients. Some physical and chemical topsoil (0-250 mm) characteristics of the experimental soils are summarized in Tables 2.1 and 4.1.

5.2.2 Soil and maize plant sampling and analysis

Topsoil samples (0 - 250 mm) were collected annually in February/March at flowering. Eight sub samples were taken within each plot between the rows and bulked as a composite sample, air-dried and ground to pass through a 2 mm sieve prior to analysis.

Soil pH (H_2O) was determined in a 1:2.5 (soil:water) suspension (Reeuwijk, 2002). Extractable acidity (H + Al) and Al were determined in a 1 M potassium chloride (KCl) extraction and titration with 0.1 M NaOH. Extractable Al was determined in the same extract by complexing it by adding 10 cm^3 NaF to the titrate, and titrating again to an end point. (The Non-Affiliated Soil Analysis Work Committee, 1990). Acid saturation was determined as the ratio of extractable acidity (Al + H) to the sum of extractable Ca, Mg, K and extractable acidity (Al + H), expressed as a percentage. Extractable P was determined according to the Bray-1 extraction method (Bray & Kurtz, 1945). The P concentrations of the extracts were determined on a continuous flow analyzer (Bray & Kurtz, 1945). The NH_4OAc (1 M, pH 7) method was used to determine the extractable cations Ca, Mg and K. The cations in solution were determined on an atomic absorption spectrophotometer (Thomas, 1982). A 0.02 M di-ammonium EDTA ($(NH_4)_2EDTA$) extract (The Non-Affiliated Soil Analysis Work Committee, 1990) was used to extract Cu, Zn, Co, and Mo were determined by ICP-MS. Water soluble B was determined by the hot water extraction method (The Non-Affiliated Soil Analysis Work Committee, 1990).

Maize leaf samples, immediately opposite and below the first ear were annually collected at flowering (end of February, beginning of March), 8 to 10 weeks after planting. The leaf samples were washed in deionized water, dried at 70ºC and milled. Nitrogen was determined by dry oxidation (Bellomonte *et al.*, 1987) using a Carlo-Erba CNS instrument. For the determination of P, K, Ca, Mg, K, Fe, Mn, Al, Cu, Zn and B, 1 g samples were wet-digested on a block digester with 1:3 (HNO_3 and $HClO_4$) and analyzed using an ICP-OES (Zasoski & Burau, 1977). For the determination of Mo, 0.5 g leaf samples were wet-digested with HNO_3 and analysed using an ICP-MS (Chao-Yong & Schulte, 1985). Above-ground dry matter biomass was determined at flowering by cutting the above-ground plant parts at the soil surface. The plant parts were dried at 65˚C to constant mass at which time they were weighed.

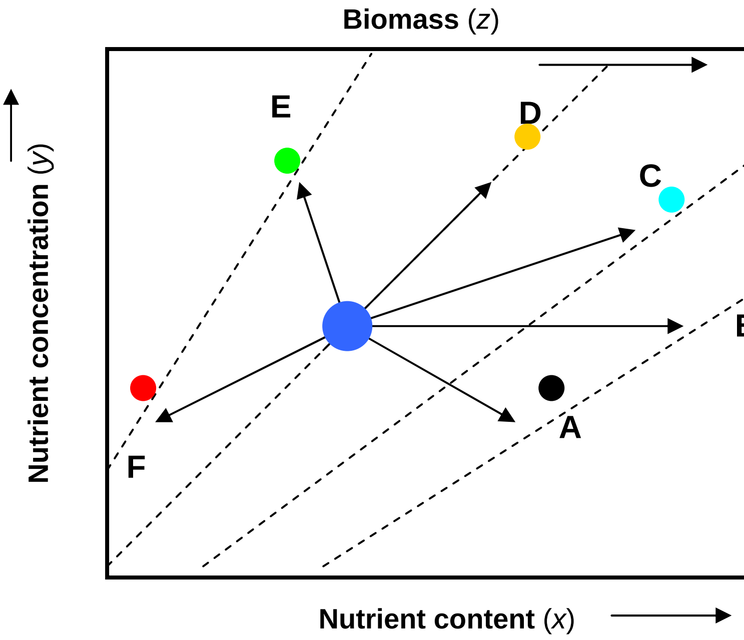
5.2.3 Statistical analysis and data interpretation

The values that will be discussed are annual replicate means per lime application level and replicated means per lime application level over years. Pearson's correlations were calculated between all variates measured. Forward selection stepwise regression was used to determine those soil properties most responsible for the variation found in maize grain yield (Genstat, 2003).

To facilitate interpretation, yield data and the chemical composition of leaf samples was interpreted using a graphical vector nutrient diagnostic technique (Timmer & Stone, 1978; Timmer & Teng, 1999, Ströhmenger, 2001). Nutrient vector analysis involves graphical representation of the relative changes in biomass, leaf nutrient contents and concentrations in leaves in response to nutrient treatments (Grundon *et al.*, 1997). The relationship (Figure 5.1) is examined by comparing growth and nutrient status of crops in a nomogram that plots biomass (*z*) on the upper axis, leaf nutrient content (*x*) on the lower axis, and corresponding nutrient concentration *(y)* on the vertical axis.

When relative yield is normalized to 100% at a specified reference sample (*i.e.* the 5 tonnes lime ha^{-1} application in this study), differences are depicted as vectors because of shifts in both direction and magnitude (Timmer & Teng, 1999). The dashed diagonals are isopleths representing change of *y* on *x,* where *z* remains unchanged (Ströhmenger, 2001). Diagnosis is based on vector direction of individual nutrients, identifying occurrence of dilution (A), sufficiency (B), deficiency (C), luxury consumption (D), toxicity (E) and antagonism (F), as depicted in Figure

5.1. Vector magnitude reflects the extent or severity of specific diagnoses, and facilitates relative ranking and prioritizing (Temmer & Teng, 1999).



Vector shift	Change in relative			Nutritional effect	Nutrient status	Possible diagnosis
	z	x	y			
A	+	+	-	Dilution	Non-limiting	Growth dilution
B	+	+	0	Accumulation	Non-limiting	Sufficiency, steady-state
C	+	+	+	Accumulation	Limiting	Deficiency response
D	0	+	+	Accumulation	Non-limiting	Luxury consumption
E	-	-, +	+	Concentration	Excess	Toxic accumulation
F	-	-	-	Antagonism	Limiting	Induced deficiency by E

Figure 5.1 Nutrient vector analysis. Interpretation of directional changes in relative biomass and nutrient status of plants contrasting in growth (Timmer & Teng, 1999).

5.2 RESULTS AND DISCUSSIONS

5.3.1 Interrelationship between maize grain yield, soil and leaf nutrients

Linear interrelationships between maize grain yield and selected soil and leaf nutrients are presented in Tables 5.1 and 5.2.

Table 5.1 Correlation matrix for the relationship between maize grain yield, soil and leaf nutrients for the Hutton soil form

	Soil									**Leaf**										
	Al	**P**	**Ca**	**Mg**	**K**	**Zn**	**Mo**	**Cu**	**B**	**N**	**Ca**	**Mg**	**P**	**K**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**	**B**
Soil P	0.11																			
Soil Ca	-0.48**	0.08																		
Soil Mg	-0.42*	-0.13	**0.95*****																	
Soil K	-0.16	-0.190	-0.08	-0.02																
Soil Zn	-0.18	0.28	**0.60*****	**0.60*****	0.17															
Soil Mo	-0.09	**0.62*****	0.13	-0.06	-0.18	0.05														
Soil Cu	-0.24	0.03	0.36	0.46*	0.23	**0.64*****	0.12													
Soil B	0.17	**-0.65*****	0.06	0.27	0.17	0.10	**-0.76*****	0.10												
Leaf N	-0.18	0.10	-0.03	-0.08	-0.04	0.02	-0.35	-0.02	-0.10											
Leaf Ca	-0.24	0.19	0.19	0.02	-0.01	-0.04	0.04	-0.48**	-0.29	0.32										
Leaf Mg	-0.41*	-0.14	**0.70*****	**0.74*****	-0.04	0.50**	0.15	0.43*	0.13	-0.21	0.06									
Leaf P	-0.15	0.32	0.14	0.06	-0.07	0.26	-0.11	0.15	-0.04	**0.85*****	0.26	0.01								
Leaf K	0.04	0.17	-0.06	-0.10	-0.39	-0.31	0.23	-0.19	-0.38*	-0.14	-0.07	-0.23	-0.07							
Leaf Fe	-0.14	-0.27	-0.25	-0.11	-0.06	-0.131	-0.22	0.20	0.05	-0.03	-0.32	-0.09	-0.32	0.31						
Leaf Al	0.05	-0.35	-0.09	0.12	-0.04	-0.12	-0.42*	0.12	0.44*	-0.04	-0.44*	0.11	0.06	0.10	**0.63*****					
Leaf Mn	0.26	-0.32	0.31	0.41*	-0.12	0.34	-0.48**	0.07	**0.63*****	0.21	0.08	0.22	0.21	-0.30	-0.14	0.07				
Leaf Zn	-0.19	-0.24	0.12	0.29	-0.05	0.16	-0.38*	0.42*	0.35	0.13	-0.14	0.24	0.10	-0.13	0.56**	0.51**	0.27			
Leaf Cu	-0.06	-0.08	0.34	0.34	-0.12	0.31	-0.37*	0.10	0.36	0.44*	0.26	0.22	0.34	-0.37*	-0.16	-0.05	**0.62*****	0.44*		
Leaf B	-0.22	-0.21	0.20	0.34	0.05	0.31	-0.34	0.36	0.34	0.35	0.01	0.27	0.40*	-0.07	0.23	0.37*	0.28	0.47*	0.14	
Yield	-0.28	-0.01	0.14	0.03	0.22	0.22	-0.18	-0.01	0.05	0.46*	0.46*	-0.06	0.30	-0.24	0.38*	-0.54**	0.20	-0.10	0.35	0.17

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

Table 5.2 Correlation matrix for relationship between maize grain yield, soil and leaf nutrients for the Oakleaf soil form

	Soil									Leaf								
	Al	**P**	**Ca**	**Mg**	**K**	**Zn**	**Mo**	**Cu**	**B**	**N**	**Ca**	**Mg**	**P**	**K**	**Fe**	**Mn**	**Zn**	**Cu**	**B**
Soil P	0.14																		
Soil Ca	**-0.95*****	-0.09																	
Soil Mg	**-0.94*****	-0.04	**0.99*****																
Soil K	-0.24	-0.01	0.45*	0.46*															
Soil Zn	0.07	0.24	0.05	0.09	0.45*														
Soil Mo	0.35	0.04	-0.24	-0.26	0.15	0.43*													
Soil Cu	0.57**	0.12	-0.57**	**-0.59*****	0.09	0.31	0.19												
Soil B	0.53**	0.10	-0.41*	-0.42*	0.07	**0.62*****	**0.70*****	0.19											
Leaf N	0.16	0.34	-0.22	-0.20	-0.09	-0.32	-0.09	0.15	-0.34										
Leaf Ca	-0.36	0.23	0.34	0.39*	0.09	-0.27	-0.37*	-0.01	**-0.69*****	**0.66*****									
Leaf Mg	**-0.76*****	0.15	**0.79*****	**0.81*****	0.20	-0.06	-0.34	- 0.48**	**-0.62*****	0.04	0.54**								
Leaf P	0.19	0.09	-0.29	-0.30	-0.34	**-0.58*****	0.14	-0.26	-0.25	**0.70*****	0.18	-0.05							
Leaf K	0.15	0.12	-0.14	-0.07	-0.06	0.37	-0.12	0.16	0.17	-0.19	-0.02	-0.22	-0.27						
Leaf Fe	0.21	-0.02	-0.19	-0.14	-0.02	0.28	0.23	-0.18	0.43*	0.15	0.01	-0.19	0.15	0.10					
Leaf Mn	0.51**	0.25	-0.36	-0.35	0.12	0.03	0.23	-0.08	0.38*	0.36	-0.01	-0.40*	0.46**	0.16	0.49**				
Leaf Zn	-0.40	0.38*	0.40*	0.43*	0.01	-0.17	0.18	-0.16	-0.56**	**0.62*****	**0.83*****	**0.69*****	0.28	-0.16	-0.12	-0.05			
Leaf Cu	0.31	0.23	-0.34	-0.32	-0.09	-0.23	0.11	0.08	-0.10	**0.88*****	0.48**	-0.15	**0.66*****	-0.22	0.47**	0.56**	0.40*		
Leaf B	0.01	0.21	-0.10	-0.10	-0.25	-0.11	0.13	0.27	-0.26	0.08	0.23	0.22	-0.13	-0.42*	-0.02	-0.44*	0.15	0.10	
Yield	-0.54**	0.24	0.49**	0.53**	0.15	-0.06	0.37*	-0.01	**-0.66*****	0.51**	**0.92*****	**0.67*****	0.04	-0.10	0.02	-0.20	**0.79*****	0.34	0.36

*P<0.05, **P<0.01 & ***P<0.001

Hutton soil form: Table 5.1 shows a strong relationship ($P<0.001$) between soil P and soil Mo ($r=0.62$). Increased P status of the soil has been found to greatly increase the absorption of Mo by plants (Podzolkin, 1967; Gupta & Munro, 1969; Blamey & Nathanson, 1975; Barnard, 1978; Thibaud & Farina, 2006). Although P and Mo are chemically similar, the size of the $H_2PO_4^-$ anion fits better than $H_2MO_4^-$ in the fixation sites and therefore the preferred $H_2PO_4^-$ fixation results in the release of Mo. Leaf P concentrations tended to increase with increasing leaf N. A negative correlation ($P<0.01$) was obtained between maize grain yield and leaf Al ($r=-0.54$), but significant ($P<0.05$) positive correlations were observed between maize grain yield and leaf N ($r=0.46$), leaf Ca ($r=0.46$) and leaf Fe ($r=0.38$), respectively.

Further analysis using stepwise regression (Table 5.3) revealed that, of these factors, leaf Fe was the most important, accounting for 33.7% of the variation in maize grain yield. Progressive addition of the variables leaf Ca, Zn, and Mg increased the explained variation to 56.2%.

Table 5.3 Summary of the forward stepwise regression analysis for yield for the two experimental soils

Variables in model	**Hutton**	
	Variance accounted for (%)	**F**
Leaf Fe	33.70	13.04***
+ leaf Ca	47.7	12.63***
+ leaf Zn	52.3	12.19*
+ soil Mg	56.2	11.90*
Yield = -0.19 – 0.00719 leaf Fe + 8.22 leaf Ca – 0.0176 leaf Zn – 0.03402 soil Mg		
	Oakleaf	
Leaf Ca	83.10	84.37***
+ soil Al	87.60	6.87*
+ leaf B	93.00	3.50ns
Yield = -1.062 + 10.388 leaf Ca – 0.461 soil Al + 0.1735 leaf B		

Oakleaf soil form: Strong negative correlations ($P<0.001$) were observed between soil Al and soil Ca ($r=-0.95$), soil Mg ($r=-0.94$) and leaf Mg ($r=-0.76$), respectively (Table 5.2). These results indicated that the high levels of Al observed in this soil were accompanied by low concentrations of Ca and Mg in soil and leaf tissues.

Improved plant growth due to an increase in leaf N resulted in increased uptake of leaf P ($r=0.70$), leaf Ca ($r=0.66$), leaf Zn ($r=0.62$), and leaf Cu ($r=0.88$), respectively. In many soils, N is the main limiting factor of growth and yield. Therefore, crops often respond to the applied nutrients, e.g.

Zn and N together, but not to Zn alone (Alloway, 2004). Strong positive correlations (Table 5.2) were found between leaf Zn and leaf Ca (r=0.83), as well as with leaf Mg (r=0.69). These somewhat contradictory results are difficult to explain because it is well-known that Ca and Mg inhibit the absorption of Zn by plant roots through their influence on soil pH when applied as calcitic or dolomitic lime (Mengel & Kirkby, 1987; Alloway, 2004).

Acidic conditions in soil often enhance the solubility of heavy metals such as Cu. Table 5.2 shows that an increase in soil Mg, accompanied with an increase in soil pH, resulted in a significant decrease in soil Cu (r=-0.59). Strong ($P<0.001$) negative relationships between soil B and leaf Ca (r=-0.62), and leaf Mg (r=-0.69), were found (Table 5.2). Previous studies have shown a sharp decrease in available B with liming (Gupta & MacLeod, 1981; Dwivedi et al., 1992), ascribed to increased soil pH rather that to the amount of Ca added through lime. Significant positive correlations ($P<0.001$) were obtained between maize grain yield vs. leaf Ca (r=0.92), as well as with leaf Zn (r=0.79), leaf Mg (r=0.69), and soil B (r=0.66), respectively.

Stepwise regression (Table 5.3) revealed that, of these factors, leaf Ca was the most important accounting for 83% of the variation in maize grain yield. Progressive addition of the variables soil Al and leaf B increased the explained variation to 93%.

5.3.2 Nutrient uptake interactions

Evidence exists to the effect that the plant's internal requirement for some nutrients, and hence its critical concentration for deficiency diagnosis, varies with the supply of other nutrients (Grundon *et al.*, 1997). Figure 5.2 (a & b) shows the vector analysis for 0 and 10 tonnes lime ha^{-1} treatments on the Hutton and Oakleaf soils relative to the 5 tonnes lime ha^{-1} treatment for the Hutton soil form, whose status was normalized to 100% to allow comparison on a common base.

Hutton soil form: The nomogram shows downward, left-pointing vectors associated with Ca and Mg, and the largest, upward right-pointing vectors associated with Fe, Al and Mn respectively, in the 0 tonnes lime ha^{-1} treatment (Figure 5.2 (a)). As indicated by Timmer and Teng (1999), the vector length increases with reduced plant biomass or the severity of decline. The results from Figure 5.2 (a) indicate that toxic build-up of Fe, followed by Al, and to a lesser extent by Mn, inhibited the uptake of Ca and Mg in the 0 lime ha^{-1} treatment. Aluminium toxicity is frequently accompanied by high levels of Fe and Mn and low concentrations of Ca and Mg in plant tissue. This is to be expected, since Al toxicity is associated with acid soil conditions where the availability of both Fe and Mn is high and where the levels of Ca and Mg are often low because of leaching. The nomogram in Figure 5.2 (a) indicates an increased uptake of Ca and Mg, and decreased uptake of Al, Mn and Fe.

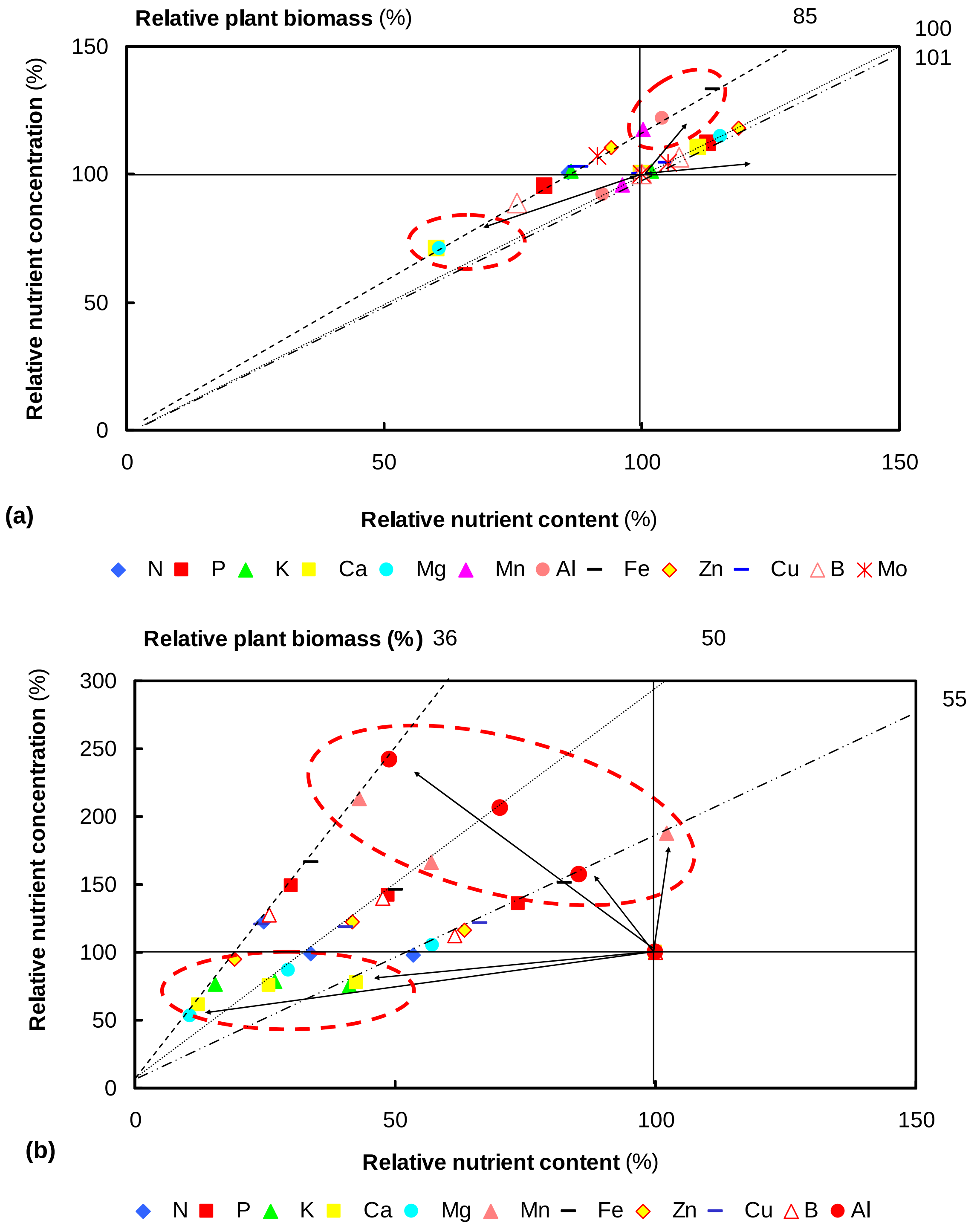


Figure 5.2 Relative response in nutrient concentration, content and dry mass of maize plants grown at differential lime rates in the (a) Hutton and (b) Oakleaf soil forms.

Calcium and Mg deficiency was corrected by the application of dolomitic lime application, which antagonistically reduced Al, Mn and Fe uptake and availability. The uptake of B was also markedly lower in the 0 lime ha^{-1} treatment (Figure 5.2 (a)) presumably due to elevated Fe, Al and Mn leaf concentrations associated with acid soils. One of the consequences of soil acidity may be the leaching of soil B. Boron in soil occurs mainly as H_2BO_3, a weak acid whose the dissociation is reduced under low pH conditions, resulting in the leaching of H_2BO_3 (Fölscher, 1978). An increased accumulation of leaf Zn, Mg, P, Ca, N, and to a lesser extent B, Mo, Cu and K, without any gain in maize biomass, was observed in the 10 tonnes lime ha^{-1} treatment (Figure 5.2 (a)). This indicated a non-limiting luxury consumption of Zn, Mg, P, Ca, N, B, Mo, Cu and K by the maize plants treated with 10 tonnes lime ha^{-1}.

Oakleaf soil form: The nomogram shows downward, left-pointing vectors associated with Ca and Mg, and the largest, upward left-pointing vectors associated with Fe, Al and Mn, respectively, in the 0 and 10 tonnes lime ha^{-1} treatments (Figure 5.2 (b)). Results in Figure 5.2 (b) show that soil Al, followed by Mn and Fe, markedly reduced the uptake of Ca and Mg. Effective liming, *i.e.* 10 tonnes lime ha^{-1} treatment, alleviated the problem of Fe, Al and Mn toxicity as shown in Figure 5.2 (b). According to Haynes (2001) several mechanisms explain the antagonistic effect of Al on Ca and Mg uptake. Firstly, Ca^{2+} and Mg^{2+} in the root apoplasm are thought to be replaced by Al^{3+} and this reduces the amount of Ca^{2+} and Mg^{2+} in the vicinity of the plasma membrane, reducing their rate of uptake. It has also been reported that Al^{3+} blocks Ca^{2+} channels in the plasma membrane and that Al^{3+} blocks binding sites for Mg^{2+} on transport proteins at the plasma membrane (Rengel & Robinson, 1989; Haynes, 2001). Antagonistic reduction of B uptake due to Al, Mn, and to a lesser extent Fe, toxicity was not observed in the Oakleaf soil.

Figure 5.2 (b) shows a right-pointing vector that was associated with high Al, and to a lesser extent Mn and a downward, left-pointing vector associated with K in all treatments (0, 5 and 10 tonnes lime ha^{-1}). This indicated that the problems associated with soil acidity were not alleviated with 5 and 10 tonnes lime applications. The predominant constraints resulting from increasing soil acidity is a severe chemical imbalance caused by toxic levels of Al, and Mn ions coupled with a parallel critical deficiency in available N, P, K, Ca, Mg, Mo, and sometimes, Zn (Fageria & Baligar, 2003). Furthermore, at low pH levels cell membranes are impaired and become more permeable. This results in a leakage of plant nutrients and particularly of K, which diffuses out of the root cells into the soil solution. This detrimental effect of high H^+ concentrations on biological membranes can be counterbalanced by Ca applied as lime (Mengel & Kirkby, 1987).

5.3 CONCLUSIONS

Nutrient vector analyses showed a toxic build-up of Fe, followed by Al, and to a lesser extent by Mn. The toxic elements depressed the uptake of and Mg in the Hutton soil. In the Oakleaf soil, Al-toxicity, followed by high levels of Mn and Fe markedly reduced the uptake of Ca and Mg. Antagonistically reduced B uptake due to Fe, Mn, and Al toxicity was observed in the Hutton soil.

Toxic levels of Al, Mn and Fe antagonistically depressed the uptake of K in the Oakleaf soil.

Generally the results indicated that soil acidity had a confounding influence on soil fertility, leaf nutrient uptake and maize growth. Aluminium-, Mn- and Fe-toxicity, respectively, and deficient levels of Ca and Mg were the factors that most adversely affected nutrient uptake and maize grain yields in the study area. The highest yields were associated with low leaf Al, Fe and Mn levels. It was also found that the uptake of leaf K and leaf B levels was decreased extensively under severe leaf Al, Mn and Fe toxicity.

6

RELATIONSHIPS BETWEEN SOIL BUFFER CAPACITY AND SELECTED SOIL PROPERTIES

6.1 INTRODUCTION

One of the main problems with soil acidity is the relationship between the total acidity of the system (*i.e.* the nature and amounts of proton donors in the solid phase) and the intensity of acidity (*i.e.* the activity of hydrogen ions in the soil solution). This relationship is defined as the soil buffer capacity (Bache, 1988). The determination of soil buffer capacity (soil BC) has long been of interest to soil chemists and crop scientists. The reason is that many crops respond positively to the addition of lime to acid soils, but because of the differences in soil BC, soils of similar pH may require vastly different quantities of lime to yield the same increase in pH. A soil's BC is furthermore also needed to understand the rate of natural soil weathering as well as the rate of soil acidification from acid-forming nitrogen fertilizers, acid rain, and acid mine waste (Bloom, 2000).

Laboratory measurement of soil BC by titration techniques is used to directly determine lime requirement (McLean *et al.*, 1966; Follett & Follett, 1983), to calibrate rapid lime requirement tests and to ascertain soil BC in acidification studies enabling calculation of acidification rates (Helyar & Porter, 1989; van Breemen, 1991; Aitken & Moody, 1994). The general factors responsible for soil BC and pH buffering in soils, include the amount of organic matter (OM) and the type of clay minerals present (Magdoff *et al.*, 1987). Soil buffering caused by the protonation and deprotonation of minerals and organic materials reduces the change in soil pH when acids or bases are added to the soil. In most soils, the general pH range of buffering by soil components is from 4.0 to 8.0. Acid buffering mechanisms include aluminosilicate dissolution at low pH and $CaCO_3$ dissolution in the upper pH range. Buffering at intermediate pH (5.0 to 7.5), which is of more interest in agriculture, is mainly by cation exchange reactions in which functional groups associated primarily with variable-charge minerals and soil organic matter act as sinks for H^+ and OH^- ions. The buffering that occurs because of organic matter is from the weakly acidic carboxylic and phenolic functional groups (Neilsen *et al*., 1995; Curtin *et al.*, 1996; Curtin & Ukrainetz, 1997, Weaver *et al.*, 2004).

Currently limited information is available on the soil properties that govern the soil BC of South African soils. Steinke *et al.* (2004) found in a study of 35 surface soils of rural and community farmers in the Eastern Cape Province of South Africa, that the soil BC was related primarily to soil organic carbon, extractable acidity (Al + H) and goethite. In the United Kingdom, soil texture and organic matter content have been used to derive buffer capacity (Bache, 1988; Aitken *et al.*, 1990), with soil BC increasing as clay and organic matter increase. Although the effect of liming on soil BC on two lime-amended soils in the study area was evaluated in Chapter 3, the relative importance of soil properties in determining the soil BC of soils in the Mpumalanga Province of South Africa has yet to be ascertained. Therefore, in order to assist in the prediction of management strategies (*e.g.* maintenance lime requirements, acidification rates) the project was extended to other soils outside the experimental plots. In this study the relationships between soil properties and soil BCs for 80 acidic soils from the Mlondozi district of Mpumalanga were investigated. The objectives of the study were to (i) determine soil BC, and (ii) examine the relationships between soil BC and selected soil properties.

6.2 MATERIAL AND METHODS

6.2.1 Soils

The data used in this study were collected from a total of 80 topsoil (0-250 mm) samples in the Mlondozi district. The soils represented the most dominant soil forms, namely Clovelly (Xantic Ferralsols) and Magwa (Humic Ferralsols), with the Hutton (Rhodic Ferralsols) and Inanda (Humic Umbrisols; FAO-ISS-ISRIC, 1998) soil forms subdominant (Booyens *et al.*, 2000).

6.2.2 Soil analysis

Topsoil samples were air-dried and ground to pass through a 2 mm sieve. A particle size analysis was performed on the <2 mm soil fraction using the pipette method (Gee & Bauder, 1986). The cation exchange capacity (CEC) was determined with 1 mol dm^{-3} ammonium acetate (NH_4OAc) extraction at pH 7. The Walkley-Black method was used for the determination of organic carbon (Walkley & Black, 1934). Extractable acidity (H + Al) and Al were determined in a 1 mol dm^{-3} potassium chloride (KCl) extraction and titration with 0.1 M NaOH. Extractable Al was determined in the same extract by complexing it by adding 10 cm^3 NaF to the titrate, and titrating again to an end point. Soil pH (H_2O) and pH (KCl) were determined in 2:5 (soil:water) and (KCl) suspension, respectively, using a combined calomel reference glass electrode and pH meter (Reeuwijk, 2002). Free oxides of iron, aluminium and manganese in soils were determined by heating 4 g of soil in a water-bath at 77 ˚C in a Na-citrate/Na-bicarbonate/Na-dithionite solution (CBD-method) and the amount of Fe, Al and Mn recorded by atomic absorption (The Non-Affiliated Soil Analysis Work Committee, 1990).

6.2.3 Potentiometric titration curves

Potentiometric titrations (Ponizovskiy & Pampura, 1993) were performed on samples that were equilibrated overnight with 1 M KCl. Each soil sample was suspended in 100 ml 1 M KCl, stirred and left overnight. The suspension was titrated with 0.05 M NaOH whilst being stirred on a Metrohm potentiograph to a pH of 8.5. The titration rate was 0.667 ml minute^{-1}. For each soil a linear regression function was fitted to the relationship between 0.05 M NaOH added and soil pH. Equation 6.1, revised from Bache (1988), was used to determine soil buffer capacity (soil BC).

$$\text{Soil BC } (\text{cmol}_c \text{ kg}^{-1} \text{ soil pH unit}^{-1}) = \Delta\,(\text{OH}^-)/\Delta\text{pH} \qquad [6.1]$$

where ΔpH is the change in pH (pH unit) due to the addition of Δ (OH^-) (cmol_c kg soil^{-1}) of base (NaOH).

Bache (1988) showed that the soil BC of any given soil is not constant over the whole pH range. Therefore in order to evaluate the effect, the soil BC was determined over limited pH ranges, namely <4.5, 4.5-6.5, 6.5-8.5 and 4.5-8.5.

6.2.4 X-ray diffraction analysis

Because soil BC is strongly affected by the content and type of clay minerals, the x-ray diffraction analyses were performed on soil samples. The samples were prepared according to the method described by Jackson (1956). X-ray diffraction (XRD) analyses were carried out on a PANalytical X'pert Pro system unit with a MPPC generator (PW 3050/609theta/theta) goniometer. Standard experimental conditions were 40 kV, 35 mA, a scanning speed of 10 min/45° 2θ and a sample spinning speed 8 sec revolution^{-1}. Relative intensities or peak heights and the width at half height of X-ray diffraction peaks were used to produce estimates of the approximate amounts of minerals present in the sample and are expressed as percentages of the total clay-size fraction.

6.2.5 Statistical analysis

Soil BC was determined over limited pH ranges, namely <4.5, 4.5-6.5, 6.5-8.5 and 4.5-8.5, and correlated with selected soil properties using Pearson's coefficient of correlation. The latter also known as the product moment correlation coefficient, is a measure of the linear relationship between two random variates ($-1<r<1$) (Draper & Smith, 1981). Forward Selection Stepwise Regression was used to find those soil properties most responsible for describing the variation found in soil BC. Principal Component Analysis (PCA) was applied to the soil data in order to identify the interrelationship between the main variates that explained the soil BC, and therefore to simplify the interpretation of the soil characteristic data. All statistical analyses were done using GenStat (2003).

6.3 RESULTS AND DISCUSSION

6.3.1 Soil characteristics

Some of the physical and chemical properties of the experimental soils are reported in Table 6.1. The soils used in this study represent a wide range of properties. The mean pH (KCl) was 1.20 times lower than the mean soil pH (H_2O), indicating that the soils used in the study contained a considerable amount of reserve acidity.

Table 6.1 The range of selected soil physical and chemical topsoil (0-250 mm) properties[1] for the experimental soils

Soil property	Range	Classes per soil property			
		1	2	3	4
pH (H_2O)	4.60-7.54	<5.0 (13)[2]	5.0-5.5 (34)	5.5-6.0 (23)	>6.0 (10)
pH (KCl)	3.72-6.42	<4.0 (31)	4.0-4.5 (32)	4.5-5.0 (9)	>5.0 (8)
Extractable Al (cmol$_c$ kg^{-1})	0-1.87	<0.5 (48)	0.5-1.0 (23)	1.0-1.5 (7)	>1.5 (2)
Extractable acidity (cmol$_c$ kg^{-1})	0-2.61	<0.5 (39)	0.5-1.5 (35)	1.5-2.5 (5)	>2.5 (1)
Acid saturation (%)	0-93.50	<20 (38)	20-40 (11)	40-60 (22)	>60 (9)
Organic C (%)	1.13-9.14	<1.5 (9)	1.5-2.0 (24)	2.0-3.0 (35)	>3.0 (12)
Clay (%)	8.30-53.10	<20 (6)	20-30 (21)	30-40 (37)	>35 (16)
BC$_{4.5\text{-}8.5}$ (cmol$_c$ kg^{-1} pH unit^{-1})	0.12-2.23	<0.25 (9)	0.25-0.5 (16)	0.5-1.0 (35)	>1.00 (20)
CEC (cmol$_c$ kg^{-1})	3.34-15.5	<5.0 (14)	5.0-7.5 (39)	7.5-10.0 (13)	>10.0 (14)
CBD-Al (%)	0.06-2.43	<0.5 (26)	0.5-1.0 (38)	1.0-1.5 (11)	>1.5 (5)
CBD-Fe (%)	0.38-7.11	<1.5 (25)	1.5-3.0 (35)	3.0-4.5 (12)	>4.5 (8)
Kaolinite (%)	32-91	<40 (2)	40-60 (39)	60-80 (36)	>80 (5)
Quartz (%)	0-52	<15 (35)	15-30 (36)	30-45 (7)	>45 (2)
Gibbsite (%)	0-44	<5 (51)	5-15 (16)	15-25 (8)	>25 (5)
Goethite (%)	0-30	<5 (26)	5-10 (18)	10-15 (23)	>15 (13)
Mica (%)	0-9	<3 (49)	3-6 (22)	6-9 (9)	>9 (0)

[1] According to the The Non-Affilliated Soil Analysis Work Committee (1990)

[2] Number of soils per class

The relatively high level of organic C indicated in Table 6.1 is the result of moderate annual temperature and high rainfall which reduces the decomposition and mineralization rates. The CEC of the soils varied from to medium (3.34 to 15.5 cmol$_c$ kg^{-1}) with a mean of 6.5 cmol$_c$ kg^{-1}.

The dominant clay mineral was kaolinite. Kaolinite is a low activity clay which has little or no permanent charge and therefore little capacity to buffer soil pH (Bloom, 2000). Soil BC data shown in Table 6.1 are comparable with the normal range found in the literature (0.38-1.34; De Sá Mendonça *et al.*, 2005).

6.3.2 Potentiometric titration curves

Figure 6.1 illustrates combined data titration curves for the main soil forms found in the study area. Titration curves followed the same general pattern as reported for surface soil horizons (Magdoff *et al.*, 1987; Steinke *et al.*, 2004).

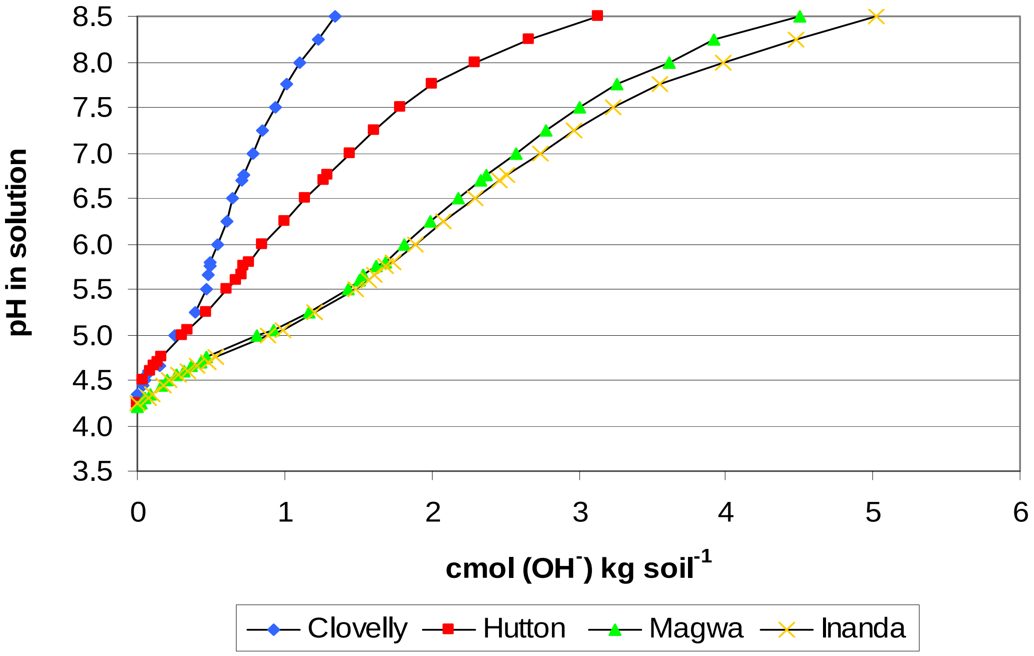


Figure 6.1 Combined titration curves for the dominant soil types.

The Hutton, Magwa and Inanda soils tended to be relatively moderately buffered in the midrange (pH 5.25-7.50) with no clear lower asymptotes and an upper asymptote up to pH 8.5. The Clovelly soil forms tended to be very poorly buffered by comparison. Similar results were found by Magdoff *et al.* (1987) for B and E horizons which tended to be moderately buffered to unbuffered in the midrange, compared to O horizons which tended to be strongly buffered in the midrange. The Inanda soils showed a tendency to be well buffered (Figure 6.1). Steinke *et al.* (2004) ascribed the differences in soil BC to the organic C content of the soils, where sites with poor buffering had a mean organic C content of 3.3% compared to 10.9% for well-buffered soils. However, in this study the organic C content varied over a relatively small range (Table 6.2). The differences in the titration curves and resultant soil BC can probably be ascribed to a combination of different factors, of which the differences in extractable acidity (0.34 vs 1.07 $cmol_c\ kg^{-1}$) and Al (0.25 vs 0.77 $cmol_c\ kg^{-1}$) that were observed between the soil forms, could make substantial contributions.

Table 6.2 Mean values of selected soil physical and chemical topsoil (0-250 mm) properties[1] for the dominant soil forms

Soil property	Soil form			
	Clovelly	Hutton	Magwa	Inanda
pH (H_2O)	5.68	5.55	5.19	5.13
pH (KCl)	4.41	4.40	3.99	4.03
Extractable Al ($cmol_c\ kg^{-1}$)	0.25	0.39	0.62	0.77
Extractable acidity ($cmol_c\ kg^{-1}$)	0.34	0.42	0.94	1.07
Acid saturation (%)	18.45	20.14	46.98	43.90
Organic C (%)	1.90	1.81	2.38	2.60
Clay (%)	29.41	30.36	33.97	40.56
$BC_{4.5\text{-}8.5}$ ($cmol_c\ kg^{-1}$ pH $unit^{-1}$)	0.53	0.68	0.86	1.13
CEC ($cmol_c\ kg^{-1}$)	6.32	5.86	7.86	9.19
CBD-Al (%)	0.58	0.62	0.77	0.89
CBD-Fe (%)	1.77	3.15	3.81	2.12
CBD-Mn (%)	0.005	0.009	0.004	0.012
Kaolinite (%)[2]	64.18	54.00	61.95	61.30
Quartz (%)[2]	19.50	16.43	16.57	12.00
Gibbsite (%)[2]	2.86	0.00	8.90	10.20
Goethite (%)[2]	10.11	14.71	6.43	10.40
Mica (%)[2]	2.32	2.57	2.33	2.00

1 According to the The Non-Affilliated Soil Analysis Work Committee (1990)

2 % of total clay

6.3.3 Soil buffer capacity over limited pH ranges vs soil properties

The relationships between soil BC for different soil pH ranges and selected soil properties are presented in Table 6.3. It was found that all soil BCs were highly significantly ($P<0.001$) correlated with clay content, log organic C content, extractable Al and acidity, log CBD-Al and Fe, and CEC, and to a lesser extent with pH (H_2O & KCl), CBD-Mn and gibbsite.

However, the soil BC of any given soil is not constant over the whole pH range (Bache, 1988; see Chapter 3). The buffer capacity reactions in soils include proton desorption and adsorption reactions by mineral and organic minerals, as well as ion exchange, dissolution and precipitation reactions. Some of the soil components are effective in buffering over a wide range of pH values, while others are effective over a limited pH range (Bloom, 2000). Therefore, the relationship of soil BC, over limited pH ranges, with selected soil properties needed to be further evaluated.

Soil BC (pH<4.5): The correlation matrix (Table 6.3) reveals that extractable acidity and Al was the best correlated with soil $BC_{(pH<4.5)}$, followed by organic C and clay content (all $P < 0.001$). Previous studies showed that the soil BC increases as pH drops below 4.5. This is mainly due to Al buffering, proton adsorption by clays and hydrous oxides (Bache, 1988; Bloom, 2000; Kauppi *et al.*, 1986). The significant correlation of organic C and clay content with soil $BC_{(pH<4.5)}$ is consistent with previous studies which showed that both of these parameters buffer pH over a wide range of pH values (Bloom, 2000; Magdoff *et al.*, 1987; Weaver *et al.*, 2004). In acid mineral soils, many of the –COOH sites in soil organic matter are taken up by Al^{3+} and this strongly bound Al has a large effect on buffering.

Soil BC (pH4.5-6.5): Soil properties found to correlate highly significantly ($P<0.001$) with soil $BC_{(pH4.5\text{-}6.5)}$, were extractable acidity and Al, which can be regarded as the primary buffering mechanism, followed by clay, CBD-Al, organic C and CBD-Fe. This is somewhat contradictory to the statement of Bache (1988) who reported that for most surface soils, pH-dependent charge associated with organic matter is the main buffering mechanism over the pH range 4.5-6.5.

Table 6.3 Correlation matrix for the relationship between soil BC and selected soil properties

	BC 4.5-8.5	**BC <4.5**	**BC 4.5-6.5**	**BC 6.5-8.5**	**pH (H_2O)**	**pH KCl**	**Extr acid**	**Extr Al**	**L Ca**	**L org. C**	**Clay**	**CEC**	**L CBD-Al**	**L CBD-Fe**	**L CBD-Mn**	**Qt**	**Kt**	**Go**
BC <4.5	**0.65*****																	
BC 4.5-6.5	**0.86*****	**0.77*****																
BC 6.5-8.5	**0.94*****	**0.48*****	**0.64*****															
pH (H_2O)	**-0.55*****	**-0.55*****	**-0.74*****	**-0.42*****														
pH KCl	**-0.47*****	**-0.58*****	**-0.65*****	-0.35**	**0.92*****													
Extr acid	**0.65*****	**0.82*****	**0.86*****	**0.48*****	**-0.75*****	**-0.66*****												
Extr Al	**0.68*****	**0.83*****	**0.87*****	**0.51*****	**-0.76*****	**-0.65*****	**0.98*****											
Log Ca	-0.21	-0.33*	**-0.47*****	-0.04	**-0.70*****	**0.64*****	**-0.72*****	**-0.69*****										
Log org. C	**0.69*****	**0.65*****	**0.58*****	**0.69*****	0.15	-0.12	**0.38*****	**0.38*****	0.03									
Clay	**0.74*****	**0.63*****	**0.62*****	**0.77*****	-0.17	-0.10	0.32**	0.32**	0.05	**0.55*****								
CEC	**0.60*****	**0.49*****	**0.44*****	**0.61*****	-0.08	-0.09	0.26*	0.23**	0.15	**0.48*****	**0.73*****							
Log CBD^{a}-Al	**0.68*****	**0.62*****	**0.60*****	**0.68*****	-0.25*	-0.15	0.36**	**0.38*****	-0.11	**0.66*****	**0.64*****	**0.39*****						
Log CBD^{a}-Fe	**0.66*****	**0.52*****	**0.50*****	**0.71*****	-0.17	-0.09	0.18	0.19	0.13	**0.53*****	**0.70*****	**0.56*****	**0.85*****					
Log CBD^{a}-Mn	**0.38*****	0.23	0.25*	**0.45*****	-0.01	0.03	0.02	0.035	0.26*	0.15	**0.46*****	**-0.58*****	**0.38*****	**0.68*****				
Quartz	-0.23*	-0.26	-0.28*	-0.18	0.31**	0.17	-0.23*	-0.21	0.18	-0.08	-0.21	-0.03	-0.29**	-0.24*	-0.01			
Kaolinte	-0.20	-0.11	-0.09	-0.23*	-0.13	-0.04	-0.07	-0.04	-0.10	-0.28	-0.17	-0.31**	-0.13	-0.16	-0.09	-0.55***		
Goethite	0.22	0.11	0.04	0.30**	0.11	0.17	-0.19	-0.16	0.30**	0.13	0.30**	0.08	0.33**	**0.41*****	0.21	-0.10	-0.14	
Gibbsite	**0.38*****	0.35*	**0.40*****	0.32**	-0.23*	-0.20	**0.43*****	**0.38*****	-0.24	**0.38*****	0.26*	0.29**	0.35**	0.25*	-0.01	-0.19	**-0.56*****	-0.18

a Sodium-citrate-bicarbonate- dithionite

* P<0.05, **P<0.01 & ***P<0.001

Forward stepwise regression analysis shows (Table 6.4) that extractable Al, clay, pH (KCl), organic C and CBD-Fe are significantly related with soil BC, with extractable Al being the most important variable, accounting for 75.2% of the variation in soil $BC_{(pH4.5-6.5)}$. Progressive addition of the variables clay, pH (KCl), organic C content and CBD-Fe increased the explained variation to 92.2%.

Soil BC (pH6.5-8.5): Clay content was found to have the highest correlation with soil $BC_{(pH6.5-8.5)}$, followed by CBD-Fe, organic C and CBD-Al (Table 6.3). Forward stepwise regression analysis showed that clay, organic C, pH (H_2O), CBD-Mn, and Ca were significantly correlated with soil $BC_{(pH6.5-8.5)}$. Clay content and organic C accounted for 68.5% of the variation in soil $BC_{(pH6.5-8.5)}$ (Table 6.4).

Table 6.4 Summary of the forward stepwise regression analysis for soil BC at different pH ranges

Soil buffer capacity pH range	Variables in model	Variance accounted for (%)	F
Soil $BC_{pH<4.5}$	Extractable Al	69.00	114.64***
	+ Clay	74.00	10.65**
Soil $BC_{pH4.5-6.5}$	Extractable Al	75.2	225.73***
	+ Clay	88.0	78.59***
	+ pH (KCl)	89.9	14.67***
	+ log Organic C	91.4	13.41***
	+ log CBD-Fe	92.2	8.29**
Soil $BC_{pH6.5-8.5}$	Clay	59.1	110.65***
	+ log Organic C	68.5	3.61***
	+ pH (H_2O)	75.4	21.64***
	+ log CBD-Mn	78.2	10.19**
	+ log Ca	79.4	5.47*
Soil $BC_{pH4.5-8.5}$	Extractable Al	80.1	299.43***
	+ log Fe-CBD	88.4	53.07***
	+ Clay	89.4	8.55**

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

Soil BC (pH4.5-8.5): In most soils, the general pH range of buffering by soil components is from 4.0 to 8.0 (Weaver *et al.*, 2004). Clay content was the best related with soil $BC_{(pH4.5-8.5)}$, followed by organic C, extractable Al, CBD-Al and CBD-Fe (Table 6.3). Bloom (2000) showed that some soil components, such as soil organic matter, oxides and hydroxides of Fe and Al, allophone, imogolite and silicate clay edges are effective in buffering over a wide range of pH values.

Organic matter is a very important component of pH buffering in surface soils, even in typical upland soils that contain very little soil organic matter (Bloom, 2000). Carboxylic acids found in soils appear to have a range of pKa values, and so contribute to buffering over the pH range from 2.0 to 7.0. The similar relationship between soil $BC_{(pH4.5\text{-}8.5)}$ and clay content (r = 0.74) and between soil $BC_{(4.5\text{-}8.5)}$ and organic C (r = 0.69) was surprising. Previous studies showed that organic matter may have a buffer capacity >300 times that of kaolinite clays (Bache, 1988; Aitken *et al.*, 1990).

Gibbsite, although not one of the primary soil properties related to soil $BC_{(pH4.5\text{-}8.5)}$, correlated significantly with soil $BC_{(pH4.5\text{-}8.5)}$ (Table 6.3). Oxides and hydroxides that accumulate in soils upon weathering are important mechanisms in the pH buffering of soils, particularly in highly weathered soils (Uehara & Gillman, 1982). The most common Al hydroxide mineral in highly weathered soils is gibbsite, $[Al(OH)_3]$ (Bloom, 2000).

Multiple regression shows (Table 6.4) that extractable Al accounted for 80.1% of the variation in soil $BC_{(pH4.5\text{-}8.5)}$. Progressive addition of the variables Fe-CBD and clay content increased the explained variation to 89.4%.

6.3.4 Interrelationships between soil properties contributing to soil BC

Principal component analysis (PCA) was used to examine the interrelationships between the major soil properties contributing to soil $BC_{(pH4.5\text{-}8.5)}$. The first axis, score [1] (SC [1]), explained 50.35% of the variation in the entire dataset, and the second axis, score [2] (SC [2]), explained 29.54% of the remaining variation. Axis 3, score [3] (SC [3]), only explained 9.68%. Table 6.5 shows which soil properties contribute to which axis. Soil BC, pH (H_2O), pH (KCl), extractable acidity and Al, acid saturation, log Ca and Mg were the strongest correlated with SC [1] and to a lesser extent correlated to SC [2] and SC [3], and will therefore contribute to SC [1] as indicated in Figure 6.2 (a-c). Similarly clay, CEC, log CBD-Fe and CBD-Mn were the strongest correlated with SC [2] and therefore will contribute to SC [2] (Figure 6.2 (a-c)).

The first axis (SC [1], *x*) was found to be positively related to buffer capacity, extractable acidity and Al, and acid saturation, and negatively related to pH (H_2O), pH (KCl), log Ca and Mg (Table 6.5). Axis 2 (SC [2], *y*), on the other hand, is positively related to mostly log C, clay, CEC, log CBD-Al, log CBD-Fe, and log CBD-Mn. The third axis (SC [3], *y*) is positively related to quartz and negatively related to kaolinite.

Table 6.5 Correlation matrix obtained from principal component analyses between the variables and some scores

Variable	**Score 1** **SC [1]**	**Score 2** **SC [2]**	**Score 3** **SC [3]**
Soil buffer capacity	**0.918**	0.232	0.093
pH (H_2O)	**-0.833**	0.243	0.142
pH (KCl)	**-0.786**	0.269	0.044
Extractable Al	**0.940**	-0.065	0.167
Extractable acidity	**0.948**	-0.076	0.186
Acid saturation	**0.914**	-0.299	0.108
Log Ca	**-0.733**	0.527	-0.048
Log Mg	**-0.735**	0.533	-0.071
Log C	0.398	**0.608**	0.199
Clay	0.416	**0.758**	-0.056
CEC	0.271	**0.758**	0.113
Log CBD-Al	0.511	**0.636**	-0.145
Log CBD-Fe	0.344	**0.815**	-0.255
Log CBD-Mn	0.076	**0.699**	-0.191
Quartz	-0.407	0.003	**0.772**
Kaolinite	0.064	-0.359	**-0.823**

Figure 6.2 (a-c) shows a diagrammatic representation of the PCA to portray the interrelationship of clay, organic C and extractable Al, with soil BC and other selected soil properties. In order to ease interpretation of the plotted diagram, each variant (clay, organic C and extractable Al) was ascribed to three classes, namely low, medium and high values as shown in Table 6.6.

Table 6.6 Low, medium and high class values for clay, organic C and extractable Al used in the diagrammatic representation of PCA in Figure 6.2

Soil property	**Class**		
	Low	**Medium**	**High**
Clay (%)	< 20	20-40	> 40
Organic C (%)	< 2	2-4	> 4
Extractable Al ($cmol_c$ kg^{-1})	< 0.29	0.29-0.59	> 0.59

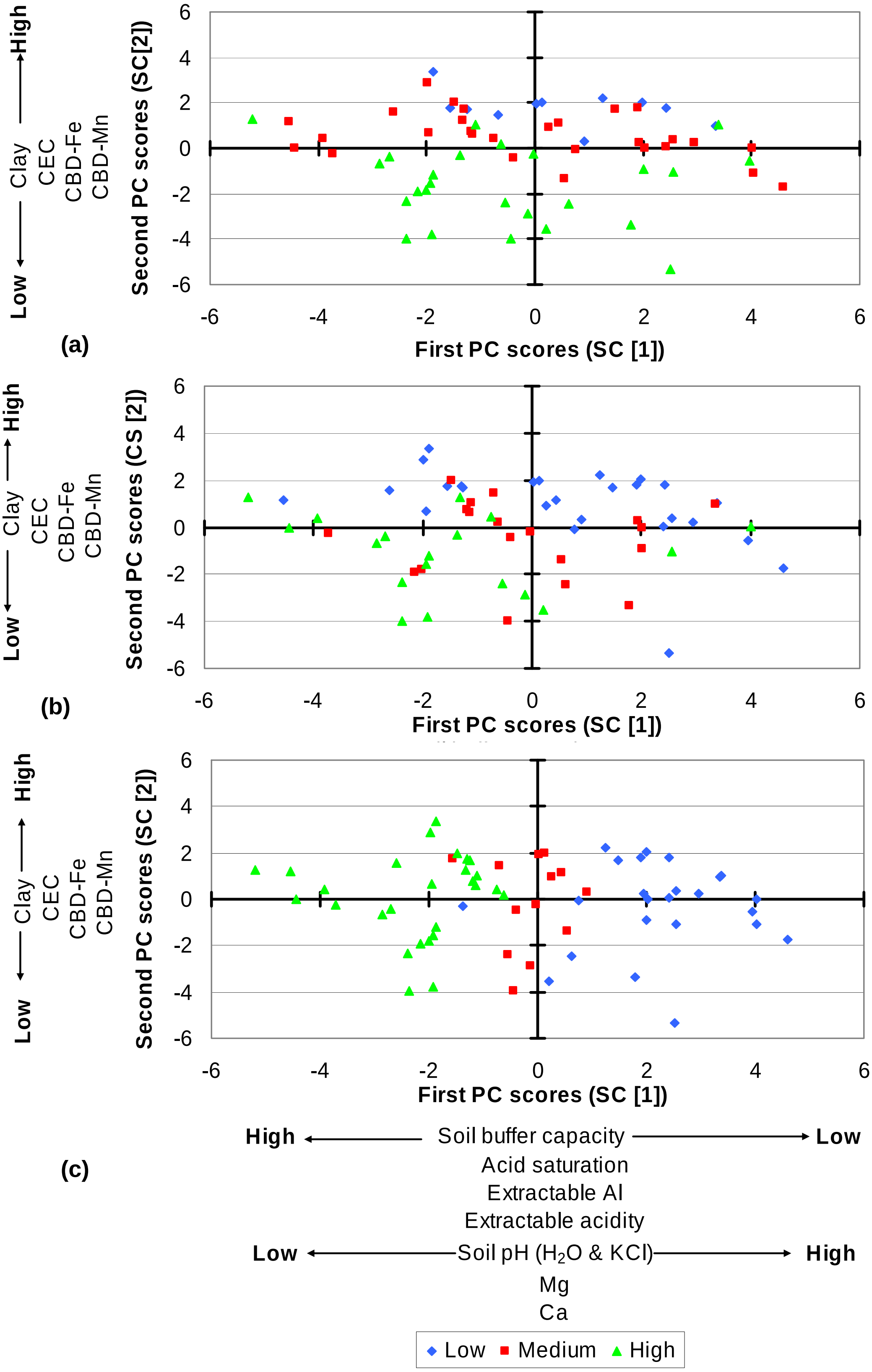


Figure 6.2 PCA evaluating the interrelationships between (a) clay content, (b) carbon content, and (c) extractable Al with soil BC and other soil properties.

Clay content: Figure 6.2 (a) shows no clear patterns with clay classes and SC [1] components. Clay content classes (low, medium and high) ranged from one extreme to the other (e.g. low soil BC to high BC) on the first score axis (SC [1]). This shows that no clear distinction could be made between clay content and first score components (e.g. soil BC, extractable acidity and Al), indicating that high clay contents could be associated with either low or high soil BC. However, a trend between clay classes and SC [2] components (e.g. log C, clay, CEC, log CBD-Al) was found (Figure 6.2 (a)) showing that soils with a low clay content (<20%) were associated with low CEC, CBD-Fe and CBD-Mn contents and soils with a high clay content (>40%) had high CEC, CBD-Fe and CBD-Mn values.

Organic C: No clear patterns between low, medium and high organic C content and both of the SC [1] and SC [2] components were observed in the studied soils (Figure 6.2 (b)).

Extractable Al: Figure 6.2 (c) shows that the low extractable Al class (<0.29 $\text{cmol}_c\ \text{kg}^{-1}$) is associated with low soil BC, extractable acidity and acid saturation values, and high pH (H_2O & KCl), Ca and Mg values. As the extractable Al increased, shown by the class high in extractable Al (>0.59 $\text{cmol}_c\ \text{kg}^{-1}$), the soil BC increased and the soil pH, Ca and Mg contents decreased. This shows that no clear distinction could be made between extractable Al and SC [2] components (Figure 6.2 (c)).

6.3.5 Relationship between dominant soil forms and selected soil properties

Figure 6.3 shows the interrelationship of dominant soil forms in the study area and selected soil properties. Although no clear clusters were observed, trends with soil type and soil properties were observed. It was found that Clovelly and Hutton soils tended to have lower soil BC, extractable Al (or acidity) and acid saturation values, and higher pH (H_2O & KCl), Ca and Mg values. Magwa and Inanda soil forms had higher soil BC, higher extractable Al (or acidity) and acid saturation values, and lower pH (H_2O & KCl), Ca and Mg values.

Figure 6.3 further shows that Clovelly soils tended to have lower clay, CBD-Fe and CBD-Mn contents, while Hutton soils tended to be higher in clay, CBD-Fe and CBD-Mn. No clear clusters were evident from the SC [2] components in Figure 6.3 for Magwa and Inanda soils, with clay, CBD-Fe and CBD-Mn contents extending from low to high values in the Magwa and Inanda soils.

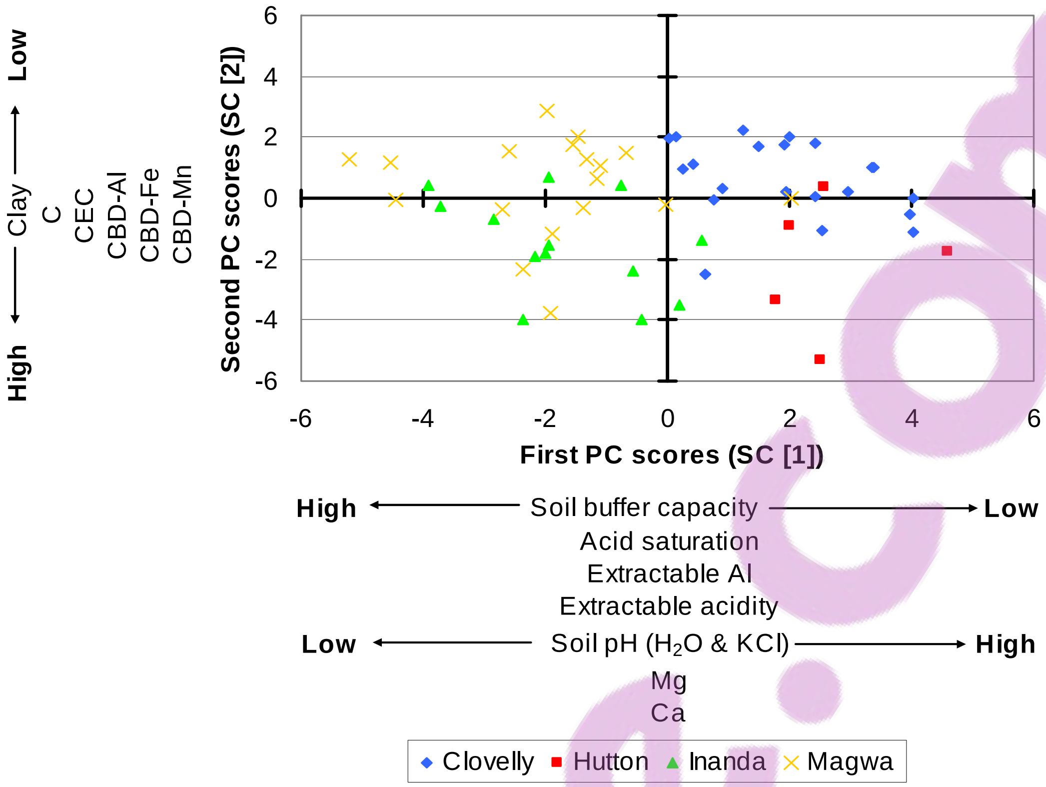


Figure 6.3 PCA evaluating the interrelationships between dominant soil forms, soil BC and other selected soil properties

The PCA results indicate that, although the Hutton and Clovelly soil forms will have the initial benefit of lower soil acidity levels and therefore a lower risk for agricultural crop production, the long-term acidification risk will be higher than that of the Magwa and Inanda soils. This is due to the lower soil BC associated with the Hutton and Clovelly soils, which means that smaller amounts of lime amelioration will be needed in these soils than in the Magwa and Inanda soils to maintain or reach a recommended soil acidity level.

6.4 CONCLUSIONS

Typical soil BCs over the general pH range 4.5 to 8.5 varied from 0.12 to 2.23 cmol$_c$ kg^{-1} pH unit^{-1}. Composite titration curves for dominant soil forms exhibited a wide range of buffering to base (OH$^-$) addition. Inanda soils showed a tendency of good buffering, while Clovelly soils revealed poor buffering. Maximum buffering for the experimental soils occurred at both pH <5.5 and >7.5, with general poor buffering between pH 5.5 to 7.5. Principal component analysis furthermore showed that Clovelly and Hutton soils tended to have lower soil BC, extractable acidity, Al and acid saturation values, and higher pH, Ca and Mg contents. Magwa and Inanda soils had higher soil BCs, extractable Al (acidity) and acid saturation, and lower pH, extractable Ca and Mg values.

It can be concluded that the more strongly buffered Magwa and Inanda soils would require more lime to neutralize soil acidity as compared to the Clovelly and Hutton soils with lower soil BC. The current knowledge of the soils in the study area indicates that there is considerable diversity in the dominant soils. Poor crop growth on Magwa and Inanda soils could be expected due to low pH and Al toxicity. It is a well-known fact that liming and adequate rates of fertilizer application are the most effective management strategies to overcome acidity and soil fertility constraints to crop production. Unfortunately, due to the high soil BC values of these soils, huge amounts of lime would be necessary to alleviate soil acidity. However, the Hutton and Clovelly soils will be more prone to soil acidification than the Magwa and Inanda soils due to the lower soil BCs of the former.

7

ASSESSING THE POTENTIAL SOIL ACIDIFICATION RISK UNDER DRYLAND AGRICULTURE

7.1 INTRODUCTION

High soil acidity and Al saturation are two of the major factors responsible for sub-optimum and growth of many crops in the Mlondozi district of Mpumalanga Province, South Africa. Highly weathered acid soils have been formed under the natural processes of weathering and acidification under high rainfall conditions. However, further acidification due to bases removed by product removal or movement of cations associated with nitrate production may intensify the soil acidity problem. Although the rate of these acidifying processes is slow under natural conditions, agricultural production systems undergo accelerated soil acidification as a result of anthropogenic inputs and outputs (Helyar, 1976; Helyar & Porter, 1989; Sumner & Noble, 2003).

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). The factors that contribute to soil acidification include the initial soil pH, soil BC, and the acidification rate (Hill, 2003). In soil acidification risk assessment, as with most agricultural risk assessments, a “problem” occurs when productivity, or the sustainability of productivity, is affected. This happens when soil pH drops below a critical pH level. Identifying areas that are at high risk of soil acidification is achieved through determining the number of years until the critical pH is reached, given the value of each of the contributing risk factors at a geographical location within the study area (Hill, 2003). It is therefore important that both the current soil pH and estimates of the rate of acid addition to soils are known, to facilitate corrective action by land users. 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 towards preventing acidification and the long-term impact of a production system.

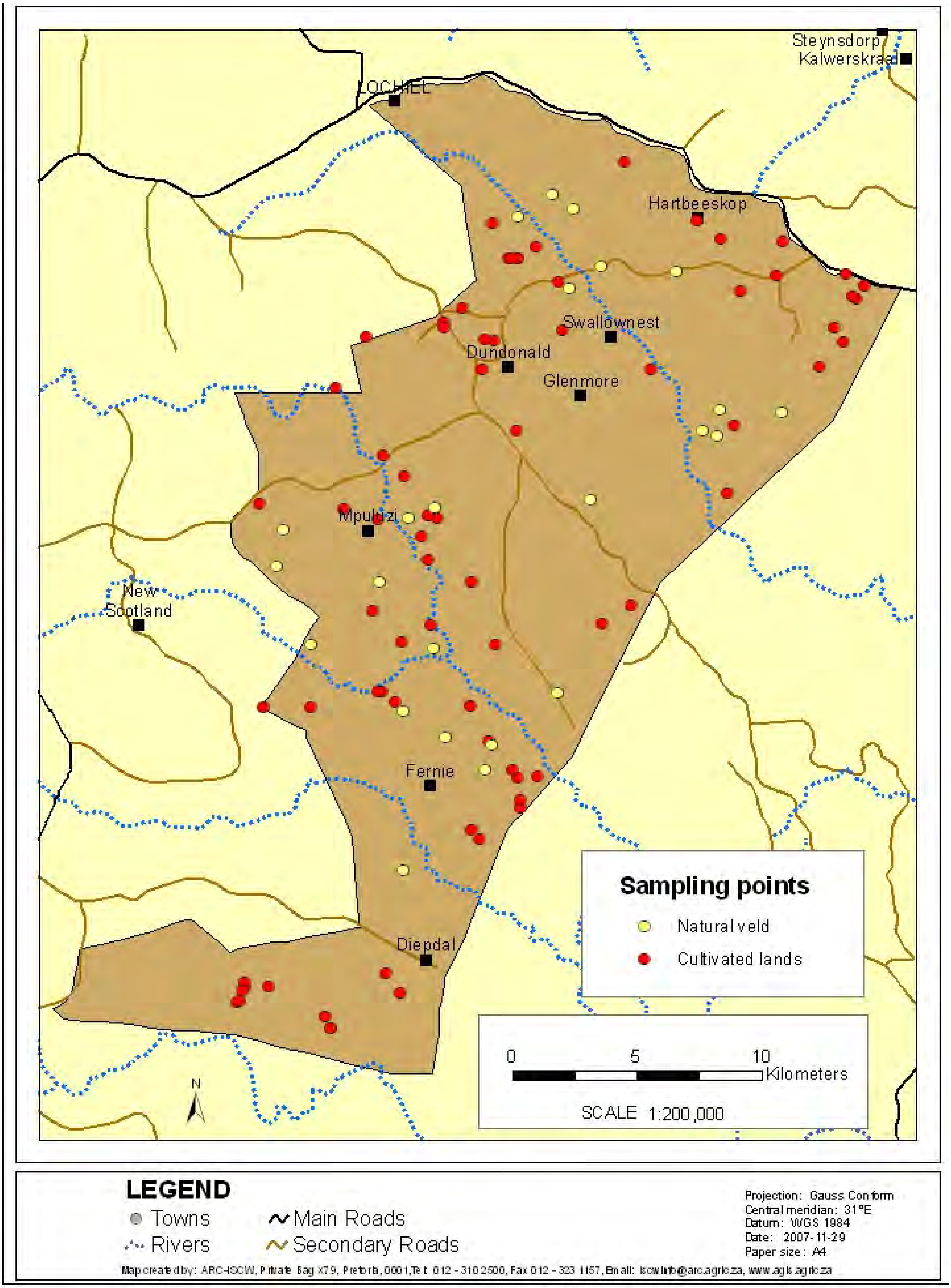
The current study was undertaken to determine the risk of soil acidification under crop production in the Mlondozi district and to model soil acidification rates based on the measurement and assumed acid inputs. The Mlondozi district formed part of a liming initiative that was started by the MDACE. Soil acidity indices, soil BC and soil acidification rates were determined for soils under crop production and natural rangeland used for cattle grazing. Furthermore, risk maps and management tools were developed for land users and extension personnel to manage soil acidification in a resource-poor farming area at Mlondozi.

7.2 MATERIAL AND METHODS

7.2.1 Study area

The Mlondozi district is situated between 26º 05’ S - 26º30’ S, and 30º44’ E - 31º00’ E and occupies a total area of 54 000 ha (Map 7.1). This 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 long-term mean annual rainfall ranges between 893 to 992 mm from north to south. Monthly average daily temperature ranges from 10.2ºC for the coldest month to 18.9ºC for the hottest month. The acid soils developed on quartz monzonite of the Mpuluzi Granite formation and the predominant clay mineral in the study area is kaolinite. Because kaolinitic clays have a relatively low CEC and consequently a low buffer capacity (Coleman & Thomas, 1964), most of the district is at high risk of soil acidification. The soils are inherently low in bases and high in kaolin and aluminium hydroxide.



Map 7.1 Location of study area and spatial distribution of sample points.

7.2.2 Soil sampling and analysis

Representative soil samples were collected from two land uses, namely natural rangeland (natural grazing; 24 samples, ≈ 50 000 ha)) and dryland crop production (66 samples, ≈ 4 000 ha). Map 7.1 indicates the spatial distribution of sample points. The sampled soils represented the most dominant soil forms, namely Magwa (Humic Ferralsols) and Clovelly (Xantic Ferralsols), with Inanda (Humic Umbrisols) and Hutton (Rhodic Ferralsols; FAO-ISS-ISRIC, 1998) soil forms subdominant.

Topsoil samples (0-250 mm) were air-dried at 23°C and ground to pass through a 2 mm sieve. A particle size analysis was performed on the <2 mm soil fraction using the pipette method. Cation exchange capacity, soil organic carbon, extractable acidity and aluminium (Al), pH (H_2O) and (KCl), and free oxides of iron (Fe), Al and manganese (Mn) were determined according the procedures of The Non-Affiliated Soil Analysis Work Committee (1990). The double buffer SMP method of McLean *et al.* (1978) was used to determine the lime requirement of the soils.

7.2.3 Soil buffer capacity

Potentiometric titrations (Ponizovskiy & Pampura, 1993) were performed on samples that were equilibrated overnight with 1 M KCl. A 50 g soil sample was suspended in 100 ml 1 M KCl, stirred and left overnight. The suspension was titrated with 0.05 M NaOH whilst being stirred on a Metrohm potentiograph to a pH of 8.5. The titration rate was 0.667 ml min^{-1}. For each soil a linear regression function was fitted to the relationship between 0.05 M NaOH added and the soil. Equation 7.1, adapted from Bache (1988), was used to calculate soil buffer capacity (soil BC).

$$\text{Soil BC } (\text{cmol}_c\ \text{kg}^{-1}\ \text{soil pH unit}^{-1}) = \Delta(\text{OH}^-)/\ \Delta\ \text{pH} \qquad [7.1]$$

where ΔpH is the change in pH (pH unit) due to the addition of OH^- (cmol_c kg soil^{-1}) as NaOH.

The soil BC calculated in Equation 7.1 was converted to (kmol H^+ $(\text{ha}_{250\ \text{mm}})^{-1}$ $(\text{pH unit})^{-1}$) using an average soil bulk density of 1300 kg m^{-3} using Equation 7.2 as suggested by Singh *et al*. (2003):

$$\text{Soil BC } [(\text{kmol H}^+\ (\text{ha}_{250\ \text{mm}})^{-1}\ (\text{pH unit})^{-1})] = (\text{BC x V x BD})/100\ 000 \qquad [7.2]$$

where V is volume of soil layer (m^3 ha^{-1}) to a depth of 250 mm; BD is bulk density (kg m^{-3}) and 100 000 to convert cmol (H^+) to kmol (H^+).

7.2.4 Acid production loads (APL), acidification rates and maintenance liming

The acid production load (kmol H^+ $(ha_{250mm})^{-1}$ $(year)^{-1}$) was calculated with Equation 7.3 as described by Helyar and Porter (1989):

$$APL = (\Delta pH/\Delta t) \times \text{soil BC} \qquad [7.3]$$

where $\Delta pH/\Delta t$ is the rate of pH decline (pH unit $year^{-1}$).

The decrease in soil pH in one year (pH $year^{-1}$) was calculated with Equation 7.4 as reported by Singh et al. (2003), using the APL and soil BC:

$$\Delta pH \text{ units } year^{-1} = APL/\text{soil BC} \qquad [7.4]$$

The number of years required for a soil to reach a critical pH value where production losses are likely to occur was calculated as expressed by Hill (2003) in Equation 7.5:

$$\text{Time (years)} = [(pH_{(current)} - pH_{(critical)}) \times (\text{soil BC})]/APL \qquad [7.5]$$

where $pH_{(current)}$ is the current pH, $pH_{(critical)}$ is the critical pH.

Maintenance liming was determined from the annual APL for the top 250 mm soil. This was achieved using the assumption that 1 mole of $CaCO_3$ neutralizes 2 moles of H^+ in the soil (Ridley et al., 1990; Dolling et al., 1994).

7.2.5 Spatial interpolation of soil properties and acidification risk

According to Hill (2003) the representation of spatial continuity of soil properties is possible by depicting the surface continuously to show gradual variations in soil properties. ArcGIS 9 (ESRI, 2006) was used to interpolate map surfaces for selected soil properties such as pH (H_2O), clay content, organic C, CEC and soil BC from 100 field sample points using the Inverse Distance Weighting interpolation method. Temporal simulation of pH changes was done using Equation 7.4 for soil pH in 2, 4, and 6 years from present pH (H_2O) values, using an average APL of 3.70 kmol (H^+) ha^{-1} $year^{-1}$ for cultivated land. Since acidification risk is strongly dependent on land use, cultivated fields were separated from natural veld by digitizing cultivated land from Spot5 imagery with a 10 m pixel size. Sample points that fell in cultivated fields were separated from points falling on natural vegetation. The cultivated fields were then interpolated using inverse distance weighting in ArcGIS 9.2 (ESRI, 2006).

In addition, the risk of pH decreasing below the critical pH value was evaluated by using Equation 7.5. Three risk classes were identified: class 1 indicates high-risk areas with pH values lower than critical pH values; class 2 indicates moderate-risk areas expected to acidify to the critical pH in less than 5 years; and class 3 is a low-risk area not expected to acidify to the critical pH within 5 years. The risk evaluation was carried out using inverse distance weighting in ArcGIS 9.2 (ESRI, 2006).

7.2.6 Statistical analysis

Data was analyzed using GenStat (2003). Pearson's correlations were calculated between all variates measured. Forward Selection Stepwise Regression was used to find those soil parameters most responsible for describing the variation found in soil BC measurements and lime requirement. In order to statistically determine critical values of properties, two procedures were followed:

(i) The broken-stick analysis procedure (GenStat, 2003) was used to statistically fit two straight line segments through datasets that exhibited two distinct populations with linear relationships per population.

(ii) Where the datasets exhibited a non-linear continuum, the Cate-Nelson procedure (Cate & Nelson, 1971) was used to determine the critical level of the *x* variable.

7.3 RESULTS AND DISCUSSION

7.3.1 General and spatial soil characteristics

Table 7.1 indicates selected soil chemical and physical properties of the main land uses in the area, namely crop production (mainly maize (*Zea mays* L.)) and natural rangeland (for cattle and goat production).

In general, soils from both land uses were acidic, with mean pH (H_2O) values of 5.53 and 5.37 for crop and rangeland soils, respectively. Natural rangeland soils were characterized by low effective cation exchange capacities (ECEC), but exhibited appreciable variable charge indicated by the difference [cation exchange capacity (CEC) – ECEC] (Table 7.1). In this context, CEC refers to the value obtained with 1 M NH_4OAC (pH 7) extraction, and ECEC is the sum of extractable cations (Al^{3+} + H^+ + Ca^{2+} + Mg^{2+} + K^+ + Na^+) (Sumner & Noble, 2003).

Soils were medium to heavy textured, with medium to high organic C content (mean C values of 2.44 and 2.10% for crop and rangeland soils, respectively; Table 7.1). Map 7.2 to 7.4 shows maps (1:200 000 scale) of interpolated organic C, clay and CEC values. In general, the organic C, clay and CEC values were highest in the north towards Hartbeeskop and in the south towards Diepdal and Fernie.

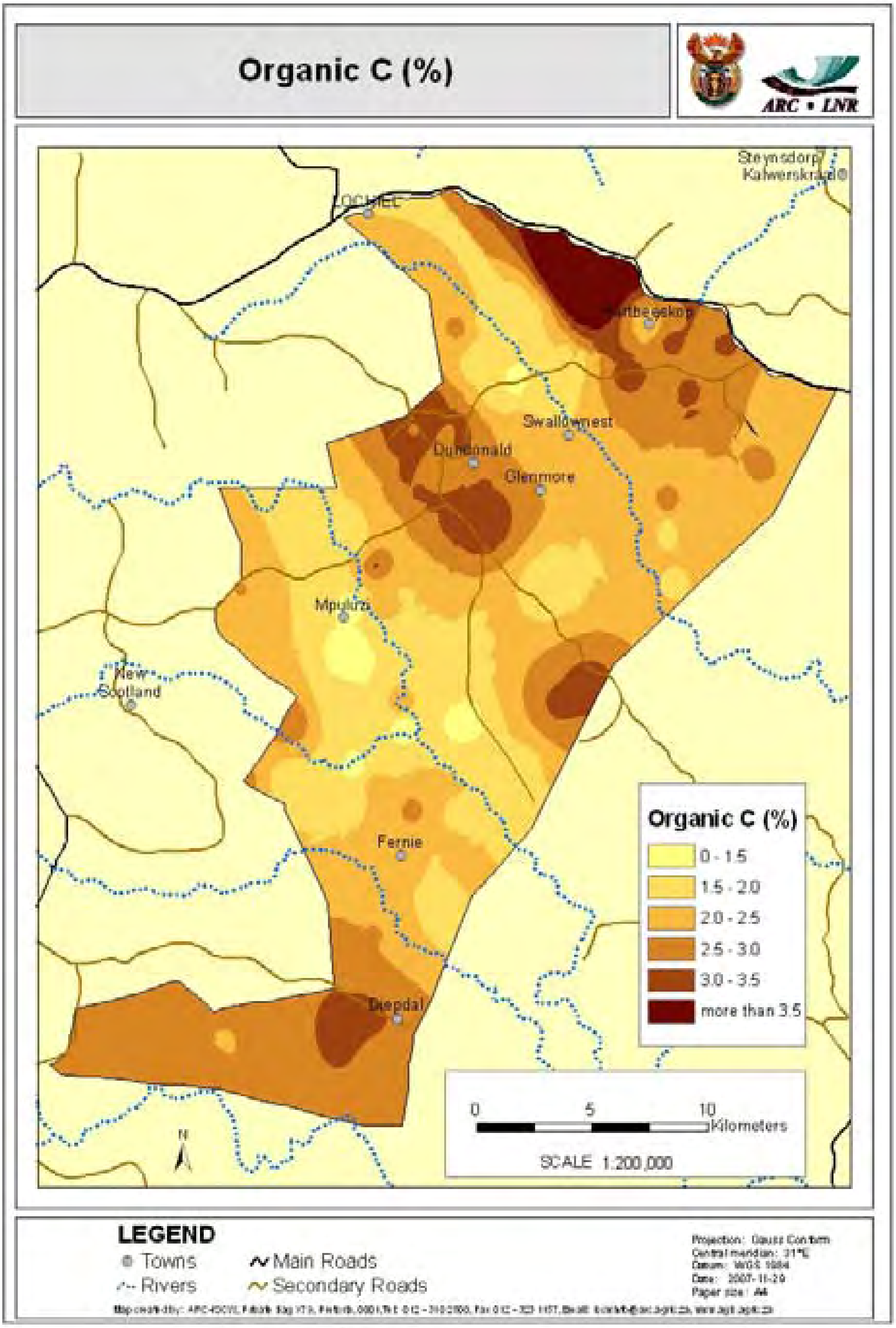
Table 7.1 Selected soil physical and chemical topsoil (0-250 mm) properties[1] for the two dominant land uses in the Mlondozi district

Soil property	Land use					
	Crop production			Natural rangeland		
	Range	Mean	Median	Range	Mean	Median
pH (H_2O)	4.60-7.54	5.53	5.46	4.69-6.18	5.37	5.30
pH (KCl)	3.72-6.42	4.31	4.16	3.87-5.24	4.11	4.07
Organic C (%)	1.14-9.14	2.44	2.30	1.13-3.18	2.10	2.03
Clay (%)	19-52	34	34	8-48	31	30
CEC ($\text{cmol}_c\ \text{kg}^{-1}$)	3.34-14.09	7.18	6.83	3.59-11.73	7.79	6.79
ECEC ($\text{cmol}_c\ \text{kg}^{-1}$)	0.78-12.72	4.99	4.58	2.62-10.31	6.00	5.31
Extractable acidity ($\text{cmol}_c\ \text{kg}^{-1}$)	0-2.61	0.60	0.42	0.05-1.50	0.68	0.56
Extractable Al ($\text{cmol}_c\ \text{kg}^{-1}$)	0-1.87	0.45	0.31	1-1.11	0.44	0.39
Acid saturation (%)	0-94	28	17	1-70	34	37
Soil BC ($\text{cmol}_c\ \text{kg}^{-1}$ pH unit^{-1})	0.22-1.91	0.75	0.71	0.21-1.54	0.68	0.59
CBD-Al (%)	0.23-2.43	0.82	0.73	0.24-1.24	0.57	0.45
CBD-Fe (%)	0.73-7.11	2.59	2.39	0.70-4.38	2.21	1.51
CBD-Mn (%)	0.00-0.02	0.006	0.005	0.00-0.04	0.007	0.003
Clay mineralogy (%)						
- quartz	0-52	18	17	7-33	17	16
- kaolinite	32-91	62	63	42-79	62	60
- mica	0-9	2	0	0-8	3	3
- goethite	0-30	10	11	0-22	8	9
- gibbsite	0-44	6	0	0-16	6	5

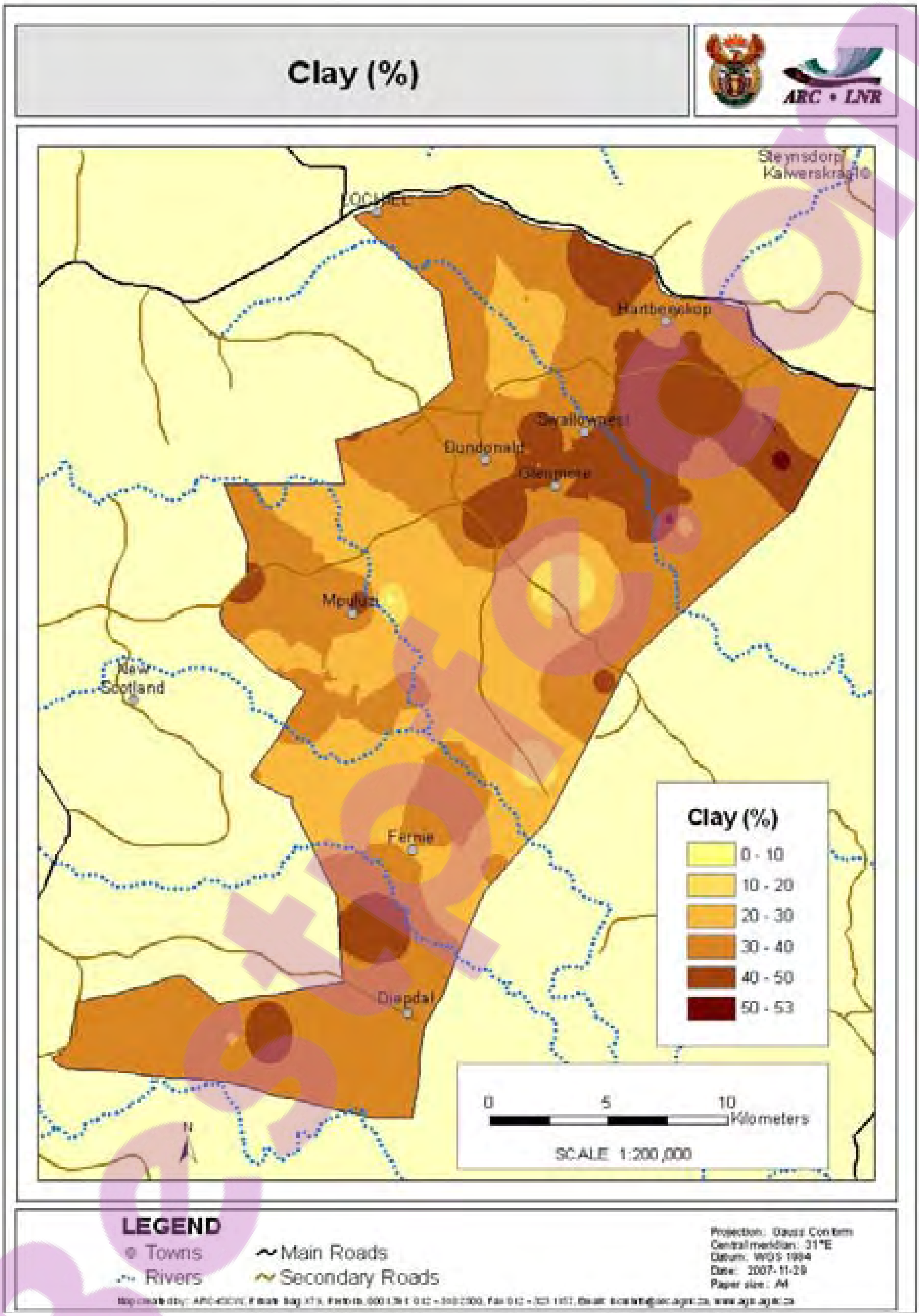
[1] According to the The Non-Affilliated Soil Analysis Work Committee (1990)

7.3.2 Soil buffer capacity

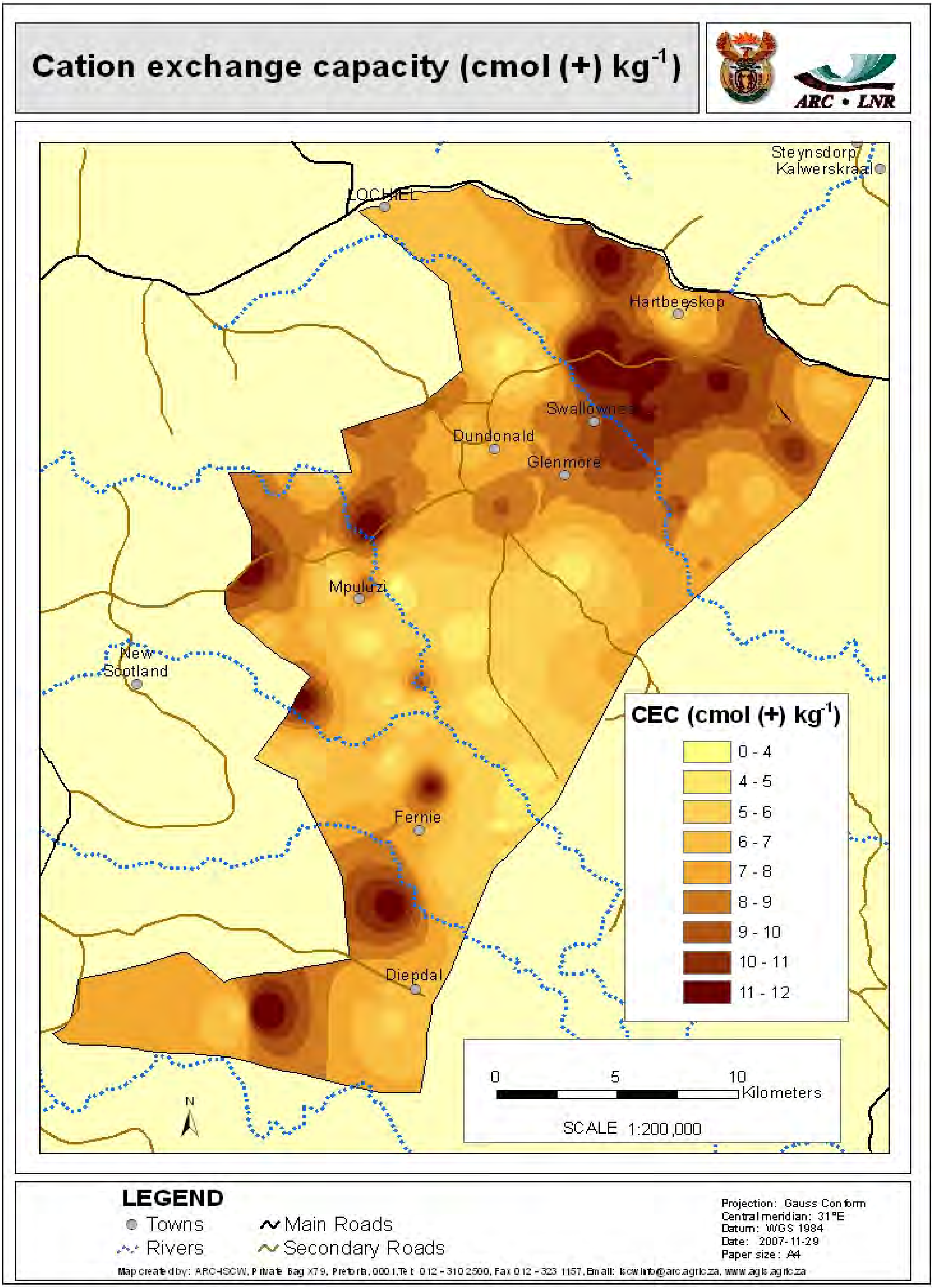
The soils in the study area were poor to well buffered (Steinke *et al.*, 2004) with soil BC values ranging from 0.124 to 2.217 $\text{cmol}_c\ \text{kg}^{-1}$ pH unit^{-1}, and means of 0.68 (rangeland) to 0.75 (crop production) $\text{cmol}_c\ \text{kg}^{-1}$ pH unit^{-1} (Table 7.1).



Map 7.2 Interpolated map (1:200 000) of organic C values of the topsoil (0-250 mm) in the Mlondozi district.



Map 7.3 Interpolated map (1:200 000) of clay values of the topsoil (0-250 mm) in the Mlondozi district.



Map 7.4 Interpolated map (1:200 000) of CEC values of the topsoil (0-250 mm) in the Mlondozi district.

Map 7.5 shows a map of the interpolated soil BC values for the study area. Areas towards the north-east around Hartbeeskop, and south around Fernie and Diepdal, showed the highest resistance to change with soil BC values greater than 0.9 $\text{cmol}_c\ \text{kg}^{-1}$ pH unit^{-1}. The highest soil BC values corresponded with high organic C, clay and CEC values as indicated in Map 7.2 to 7.4.

It was shown in Chapter 6 that clay content, organic C, extractable Al, CBD-Al and CBD-Fe were highly significantly (P<0.001) correlated with soil $\text{BC}_{(4.5\text{-}8.5).}$ Forward stepwise multiple linear regression analyses indicated that extractable Al, CBD-Fe, clay content and pH (H_2O) accounted for 91.4% for the variation in soil BC (Table 7.2). The relationship is given by Equation 7.6.

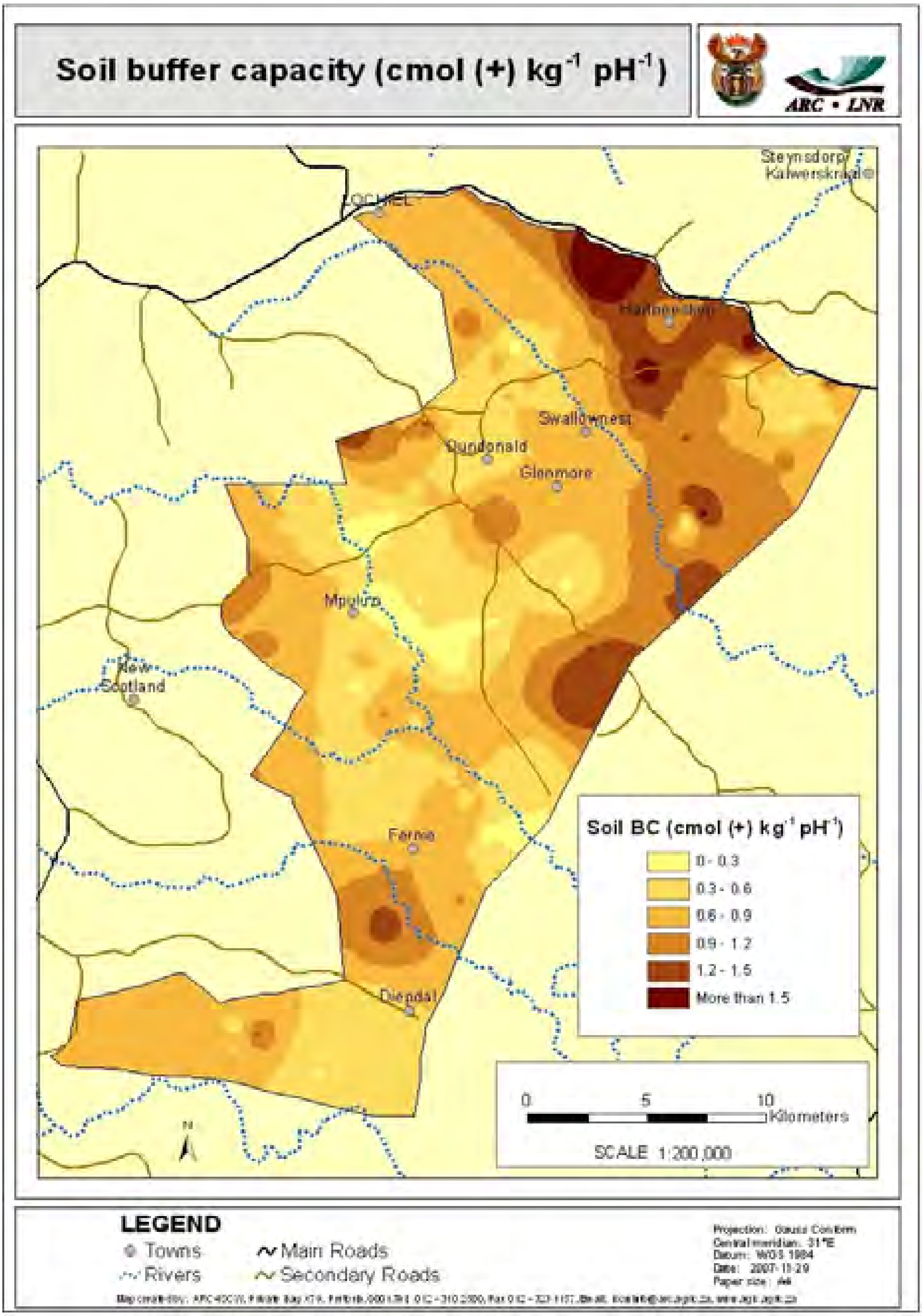
$$\text{BC} = 0.842 + 0.653(\text{Al}) + 0.109(\log\text{CBD-Fe}) + 0.0085(\text{clay}) - 0.13(\text{pH}\ (H_2O)) \qquad [7.6]$$

where soil BC is buffer capacity ($\text{cmol}_c\ \text{kg}^{-1}$ pH unit^{-1}), Al is extractable Al ($\text{cmol}_c\ \text{kg}^{-1}$), $\log_e$CBD-Fe (%), clay (%) and pH (H_2O).

Table 7.2 Summary of the forward stepwise regression analysis for soil BC and lime requirement (LR)

Independent variable	Dependent variable	Variance accounted for (%)	F
Soil BC	Extractable Al	80.1	0.187***
	+ Fe-CBD	88.4	0.143***
	+ clay	89.4	0.136**
	+ pH (H_2O)	90.3	0.131*
LR	Extractable Al	57.6	2.00***
	+ (clay/(organic C x clay))	78.2	1.44***
	+ (organic C/clay)	84.6	1.21**
	+ pH (H_2O)	87.0	1.11*

*** P < 0.001, ** P < 0.01, * P < 0.05



Map 7.5 Interpolated map (1:200 000) of soil BC values of the topsoil (0-250 mm) in the Mlondozi district.

Figure 7.1 shows a strong relationship between soil BC, determined by potentionmetric titrations, and predicted soil BC values determined from Equation 7.6. The high coefficient of determination (R^2=0.92) suggests that this relationship could be used to determine soil BC values in the study area. The prediction of soil BC values attained maximum accuracy at a measured soil BC value of 0.37 $cmol_c$ kg^{-1} pH $unit^{-1}$. A slight over estimation of soil BC was detected below this value and an under estimation of soil BC above this value.

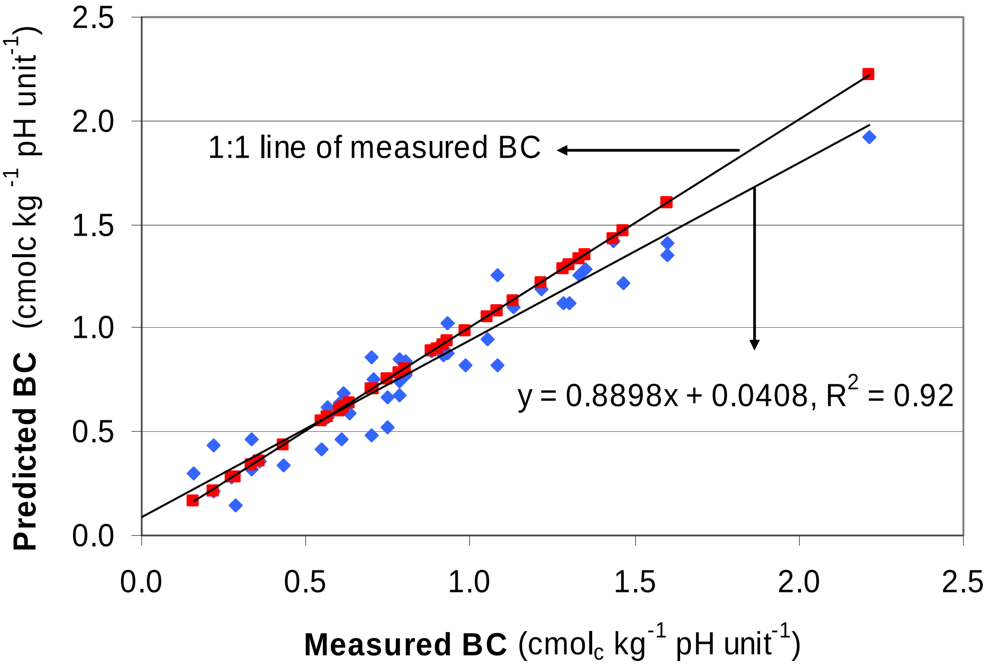


Figure 7.1 Relationship between measured soil BC determined by potentiometric titrations and predicted soil BC according to Equation 7.6.

7.3.3 Critical soil acidity indices

The relationships between pH and extractable acidity (Al + H), and Al were used to assess the critical pH values where (Al + H) and Al-toxicity is likely to be a problem. Linear components of extractable (Al + H), Al and pH relationships for all the soils were defined by broken-stick techniques. Figure 7.2 indicates that intercepts for the two lines occurred at pH (H_2O) = 5.68 and pH (KCl) = 4.25 for extractable (Al + H), and pH (H_2O) = 5.67 and pH (KCl) = 4.29 for extractable Al.

Extractable (Al + H) values of 0.27 and 0.25 $cmol_c$ kg^{-1} were recorded at pH (KCl) and pH (H_2O) values of 4.25 and 5.68, respectively (Figure 7.2). The relationship shows that when the soil pH was 4.29 (KCl) and 5.68 (H_2O), the extractable Al was 0.13 and 0.17 $cmol_c$ kg^{-1}, respectively. At pH (KCl)=4.29 and pH (H_2O)=5.68, the extractable Al was essentially eliminated and Al toxicity most likely would not be a problem for crop production in the Mlondozi district. Above this pH, extractable Al levels were low and regression slopes approached zero.

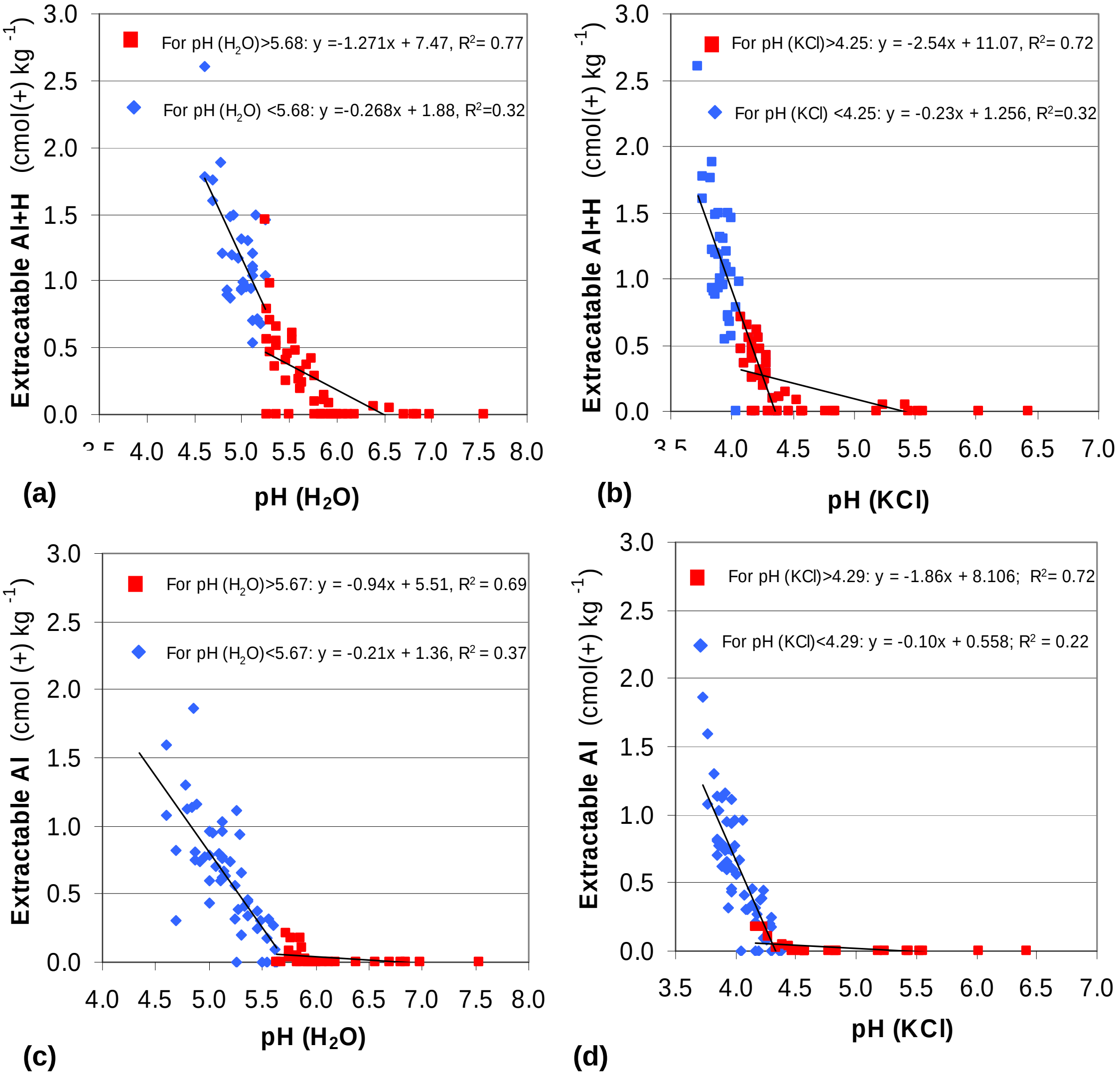


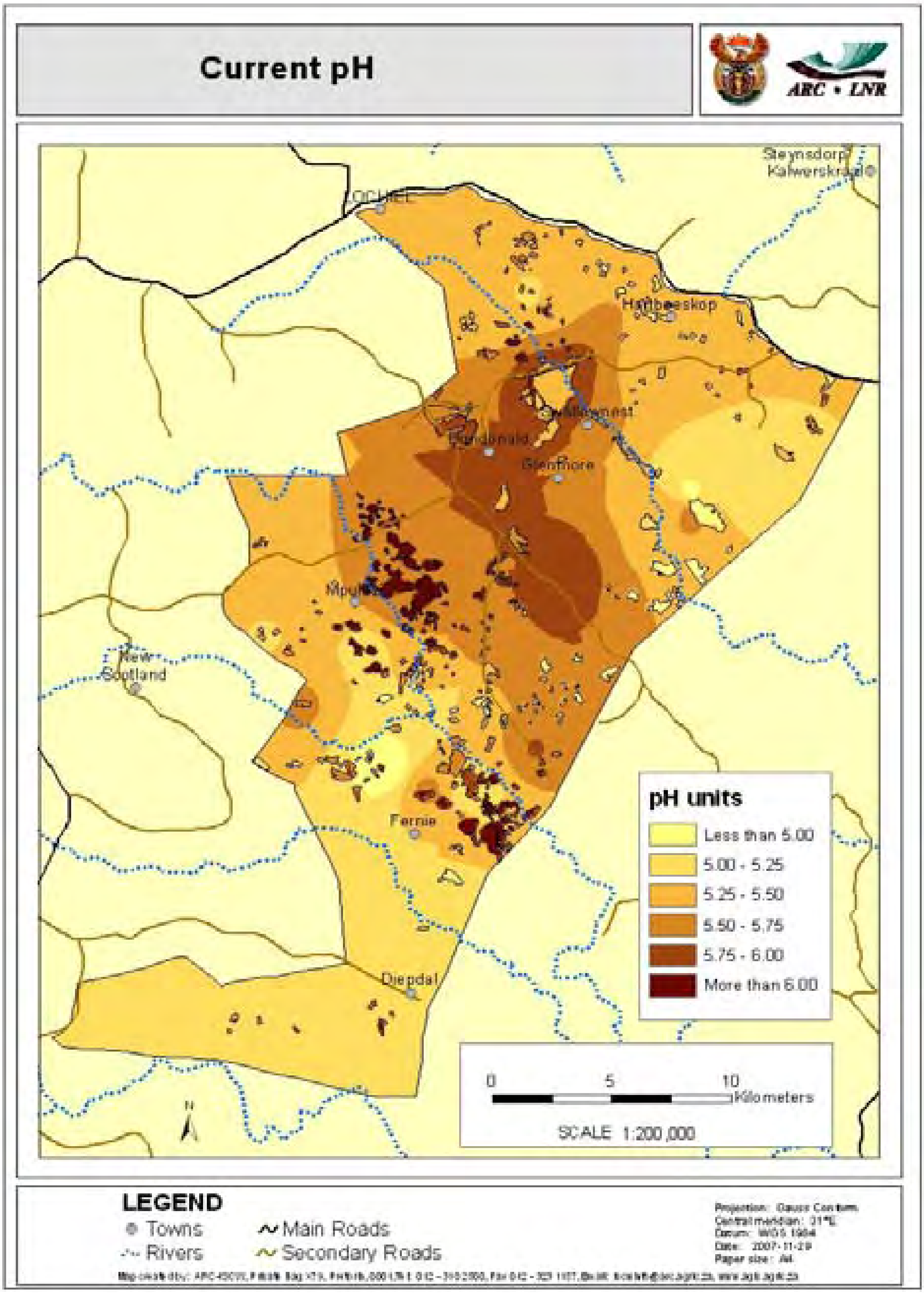
Figure 7.2 Critical soil pH values by means of broken-stick analysis between (a) pH (H_2O) and extractable (Al + H), and (b) pH (KCl) and extractable (Al + H), (c) pH (H_2O) and extractable Al and (d) pH (KCl) and extractable Al.

This observation is consistent with previous observations that extractable Al was essentially eliminated above pH (H_2O) 5.5 (Coleman & Thomas, 1967; Sanchez, 1976; Juo, 1977; Farina *et al.*, 1980).

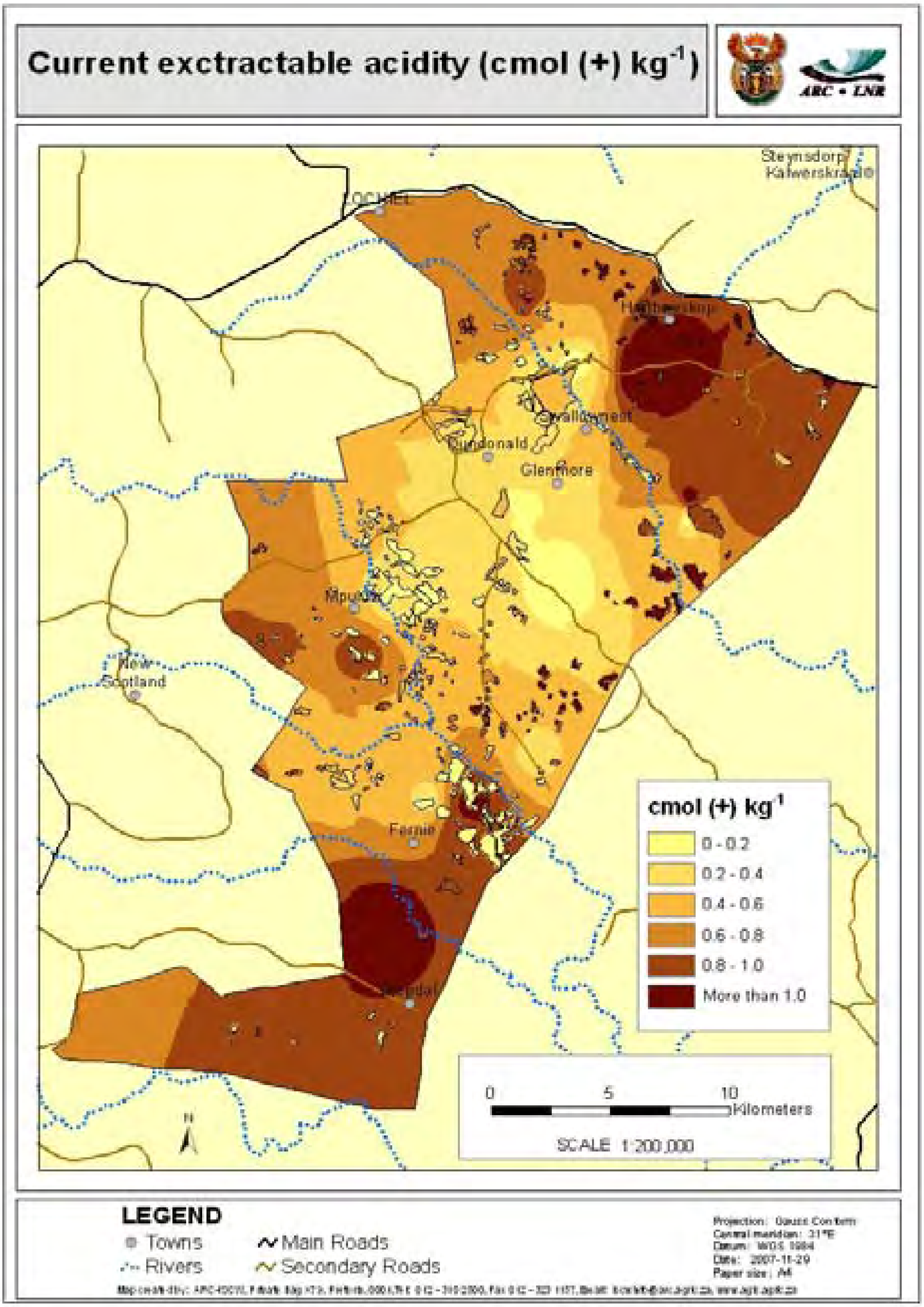
7.3.4 Actual soil acidity indices and lime requirement (LR)

Actual pH (H_2O) and extractable acidity ($cmol_c\ kg^{-1}$) interpolated maps (1:200 000 scale) are shown in Maps 7.6 and 7.7. In general, lower soil pH and higher extractable acidity values for natural veld were recorded in the north-east near Hartbeeskop and to the south of the district around Fernie and Diepdal. There was no clear trend in soil pH and extractable acidity values for cultivated fields with values that varied from lower, similar and higher than surrounding baseline values of natural veld.

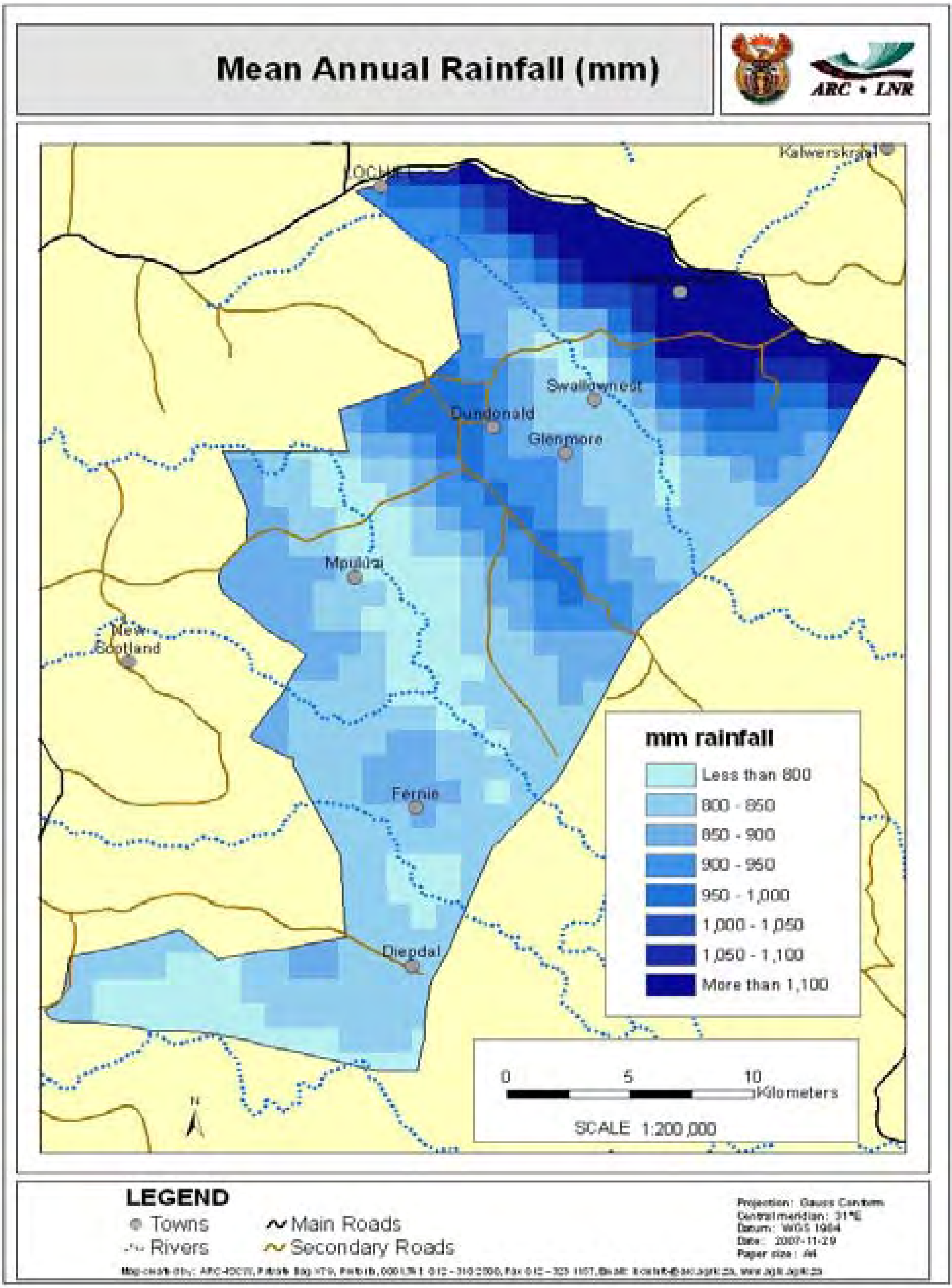
Soil acidity in natural veld, as indicated by pH and extractable acidity, shows a positive relationship with soil BC values (compare Maps 7.5, 7.6 and 7.7). Soils with higher soil BC are characterized by higher organic C and clay contents. When comparing Maps 7.6 and 7.7, with 7.8, actual soil pH and extractable acidity values show to negatively correspond with rainfall patterns in the district. Areas with low soil pH and higher extractable acidity values in the north correspond with higher rainfall, due to the leaching of appreciable amounts of extractable bases from the soil. The important correlation between soil acidification and rainfall has been highlighted by Helyar *et al.* (1990). They further showed that a soil layer may acidify by net acid production from acids produced in the inorganic and organic carbon cycles, or in the N, Fe, S, Al and Mn cycles. Other nutrient cycles are usually responsible for only minor amounts of acid production. Leaching of nitrate produced from the nitrification of organic N compounds will have a net acidifying effect because: (i) the nitrification process produces H^+ and NO_3^-, and (ii) if the NO_3^- is leached, usually with Ca^{2+} as balancing cation, the net effect is acidification. Increased leaching also leads to increased net losses of HCO_3^-, OH^-, H^+, Al^{3+} and Mn^{2+} from a soil layer. Therefore, the correlation between soil acidity indexes and rainfall partly reflects the role of leaching in the transport of organic anions and nitrate from the upper soil layers downward in the soil profile.



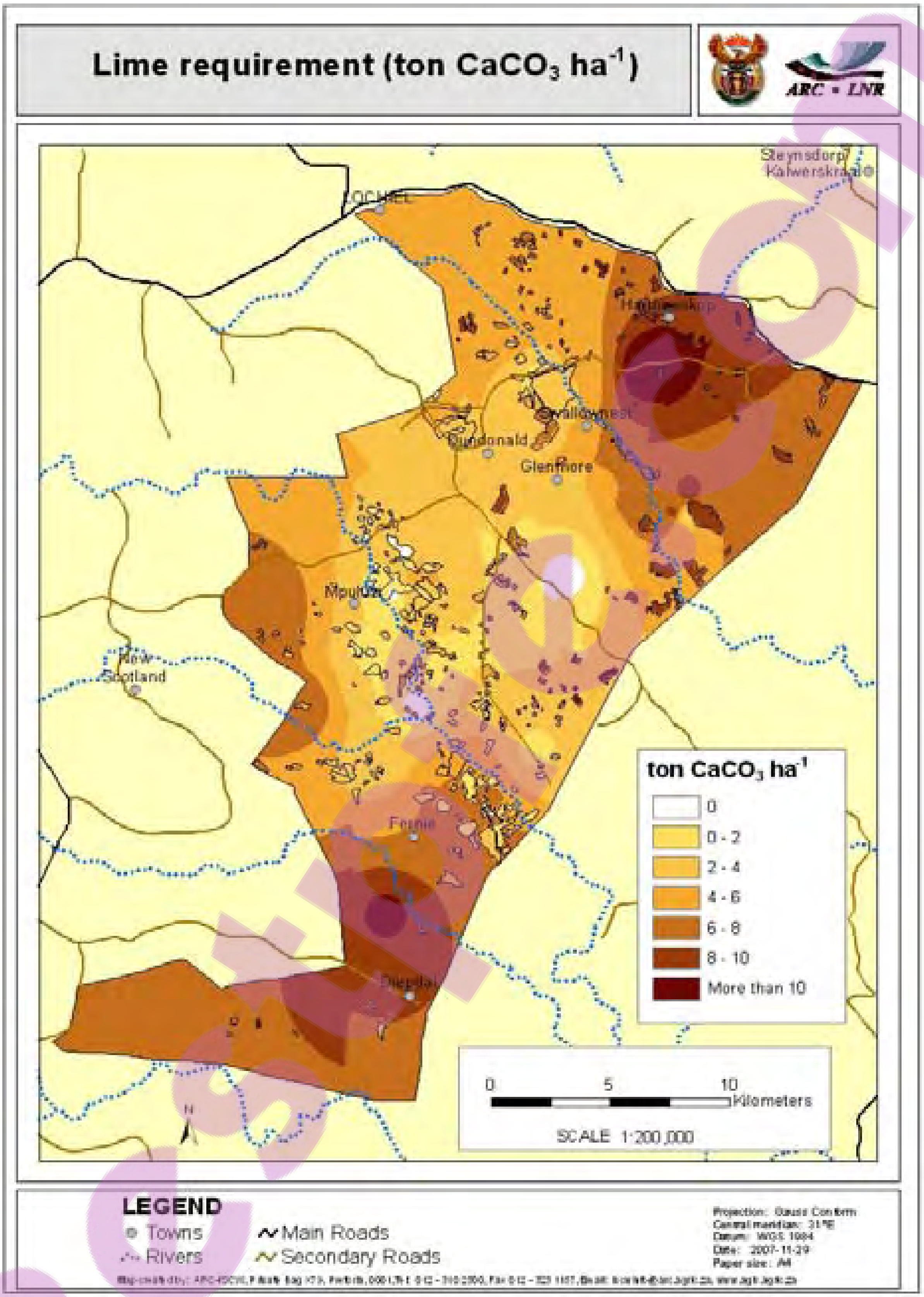
Map 7.6 Interpolated maps (1:200 000) of current pH (H_2O) for the topsoil (0-250 mm) in the Mlondozi district.



Map 7.7 Interpolated maps (1:200 000) of current extractable acidity (cmol$_c$ kg^{-1}) values for the topsoil (0-250 mm) in the Mlondozi district.



Map 7.8 Interpolated maps (1:200 000) of annual rainfall in the Mlondozi district.



Map 7.9 Interpolated maps (1:200 000) of lime requirement (tonnes $CaCO_3$ ha^{-1}) from current pH (H_2O) to pH (H_2O) 6.0 in the Mlondozi district.

The double buffer SMP method (McLean *et al.*, 1978) was used to determine lime requirements to attain a pH (H_2O) of 6.0. Hauman (1981) indicated in a study of 30 topsoil samples of the Highveld region in South Africa that this method most accurately predicted incubation lime requirement.

Table 7.3 reveals that properties such as extractable acidity (Al +H) or Al, organic C, pH (H_2O) and acid saturation are individually highly correlated ($P<0.001$) with lime requirement. Forward selection stepwise regression analysis (Table 7.2) was used to assess the contribution of various soil parameters to lime requirement as given by Equation 7.7. The regression model shows that extractable Al accounts for 57.6% of the variation in lime requirement. Progressive addition of the variables clay (%), organic C and pH (H_2O) increased the explained variation to 87.0%.

$$LR = -1.75 + 3.07(Al) - 17.45(1/(OC) - 66.7(OC/clay) + 3.45(pH(H_2O)) \qquad [7.7]$$

where LR is lime requirement (tonnes pure $CaCO_3$ ha^{-1}), Al is extractable Al ($cmol_c$ kg $soil^{-1}$), clay is the clay % and OC is organic C (%). The high coefficient of determination suggests that these relationships would prove to be satisfactory predictors of LR as shown in Figure 7.3. The prediction of LR values attained maximum accuracy at a measured lime requirement of 6.15 tonnes $CaCO_3$ ha^{-1}. A slight overestimation of lime requirement was detected below this value and an underestimation of lime requirement above this value.

Map 7.9 shows a map of the interpolated lime requirement values for the study area. Soils with high lime requirement values corresponded with areas of high soil BC values (compare Maps 7.5 and 7.9). Areas around Hartbeeskop and Diepdal showed the highest lime requirement values of 8 tonnes $CaCO_3$ ha^{-1} and higher to raise pH (H_2O) values to 6.0 to a depth of 0-250 mm.

Table 7.3 Correlation matrix between lime requirement (LR), acidification rates (Δ pH unit year^{-1}) and selected soil properties

	LR	Acid rate	pH (H_2O)	pH (KCl)	Extr. Ac.	Al	Acid Sat.	Ca	Mg	Org. C	Clay	CEC	ECEC	CBD-Al	CBD-Fe	CBD-Mn
Acid. rate	-0.154															
pH (H_2O)	**-0.627*****	**0.724*****														
pH(KCl)	-0.120	**0.628*****	**0.881*****													
Extr. Ac.	**0.686*****	**-0.595*****	**-0.847*****	**-0.813*****												
Al	**0.717*****	**-0.607*****	**-0.855*****	**-0.806*****	**0.978*****											
Acid sat.	0.105	**-0.531*****	**-0.862*****	**-0.832*****	**0.940*****	**0.905*****										
Ca	-0.037	0.087	**0.456*****	**0.492*****	**-0.523*****	**-0.493*****	**-0.599*****									
Mg	0.005	0.093	**0.520*****	**0.526*****	**-0.503*****	**-0.487*****	**-0.597*****	**0.939*****								
Org. C	**0.682*****	**-0.428*****	-0.288*	-0.224	**0.411*****	**0.431*****	0.198	-0.026	0.002							
Clay	**0.605*****	**-0.562*****	-0.297*	-0.127	0.298*	0.300**	0.117	0.158	0.202	**0.716*****						
CEC	0.297	**-0.408*****	-0.104	-0.030	0.221	0.197	0.044	0.383**	**0.480*****	**0.550*****	**0.744*****					
ECEC	-0.178	**-0.495*****	-0.339**	-0.282*	**0.492*****	**0.432*****	0.358**	-0.075	0.036	**0.581*****	**0.708*****	**0.879*****				
CBD-Al	0.385*	**-0.466*****	-0.361**	-0.248*	**0.393*****	**0.404*****	0.276*	-0.057	-0.047	**0.722*****	**0.678*****	**0.458*****	**0.511*****			
CBD-Fe	0.285	**-0.417*****	-0.105	0.062	0.056	0.072	-0.093	**0.452*****	**0.463*****	**0.551*****	**0.799*****	**0.801*****	**0.635*****	**0.637*****		
CBD-Mn	-0.336	-0.317**	-0.002	0.072	-0.001	0.017	-0.143	**0.466*****	**0.523*****	0.331*	**0.564*****	**0.810*****	**0.635*****	0.286*	**0.750*****	
Kt	0.397*	0.016	-0.181	-0.101	0.016	0.039	0.067	-0.056	-0.083	-0.300*	-0.116	-0.224	-0.251	-0.177	-0.245	-0.144

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

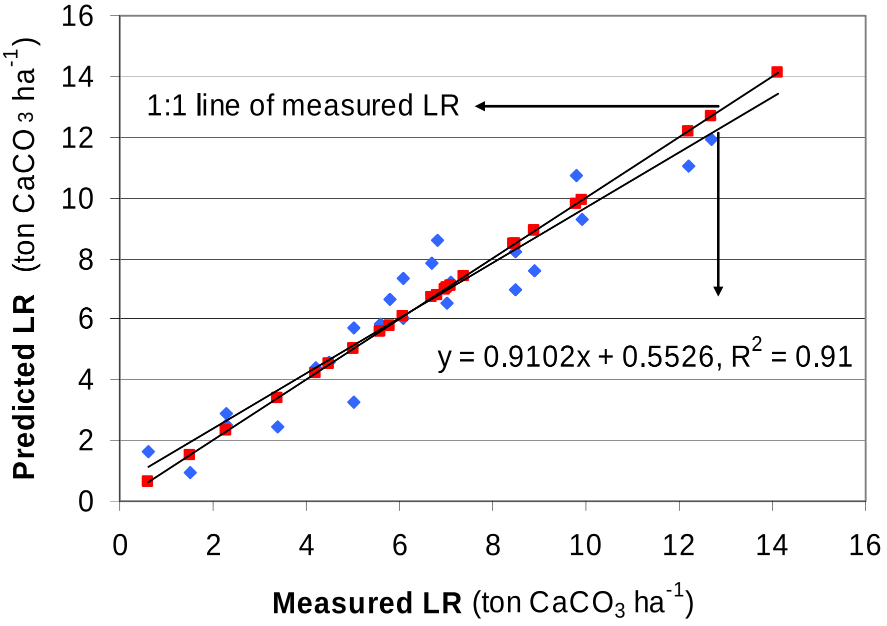


Figure 7.3 Relationship between measured lime requirement (tonnes $CaCO_3$ ha^{-1}) and predicted lime requirement according to Equation 7.7.

7.3.5 Acid production load (APL)

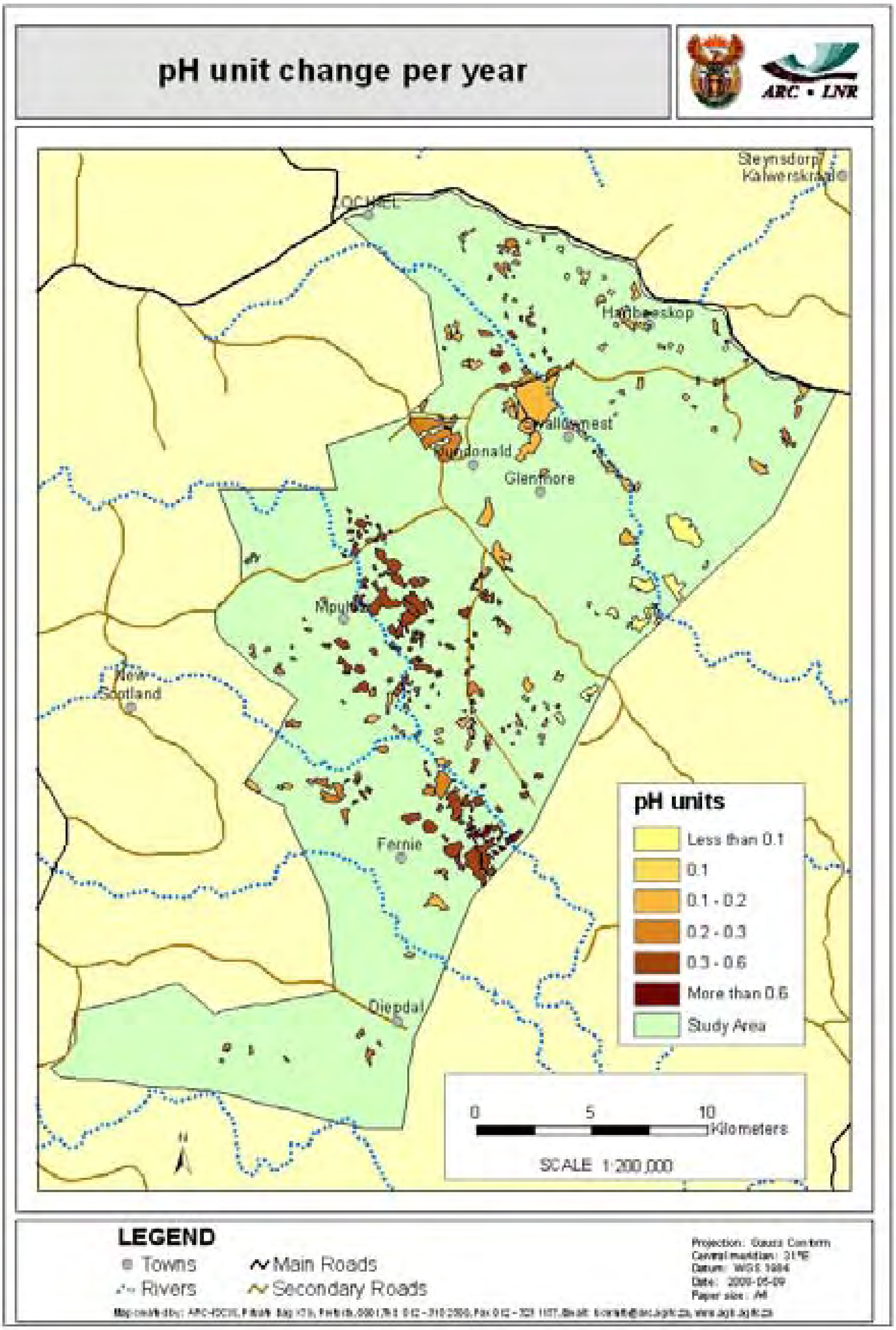
In order to simulate future soil acidification, it is necessary to determine the APL and acidification rates. The acidification rate is a factor of net acid production, and loss of alkalinity from the soil system (Hill, 2003). Medium-term changes in soil pH (H_2O) values for 35 dryland crop production sites (mainly maize) were used in the study area to determine APL, (using Equation 7.3), to a 250 mm depth. Acid production loads varied from 0.21 to 10.31 (mean of 3.70) kmol (H^+) ha^{-1} year^{-1}, depending on the production system and fertilizer inputs. Therefore, an APL value of 3.70 (mean of measured APLs) for cultivated land was used in the study to simulate acidification rates for the Mlondozi district. The lime required to balance the APL to 250 mm depth varied between 97 and 527 kg $CaCO_3$ ha^{-1} year^{-1}, with a mean of 190 kg $CaCO_3$ ha^{-1} year^{-1} in the crop production sites. The APLs recorded in the study (mean of 1.39 kmol (H^+) ha^{-1} year^{-1} to a depth of 100 mm) were similar to APLs recorded by Helyar *et al.* (1990) under continuous wheat/fallow rotation to a depth of 100 mm. Helyar *et al.* (1990) showed that the lowest acid production of -0.5 to 5.1 kmol (H^+) ha^{-1} year^{-1} was measured under a continuous wheat/fallow rotation where little or no acidification occurred. The highest rates of APL measured were associated with ammonium sulphate fertilizer use on rice (7.9 to 10.4 kmol (H^+) ha^{-1} year^{-1}) and kikuyu pastures (21.3 kmol (H^+) ha^{-1} year^{-1}).

7.3.6 Acidification risk assessment

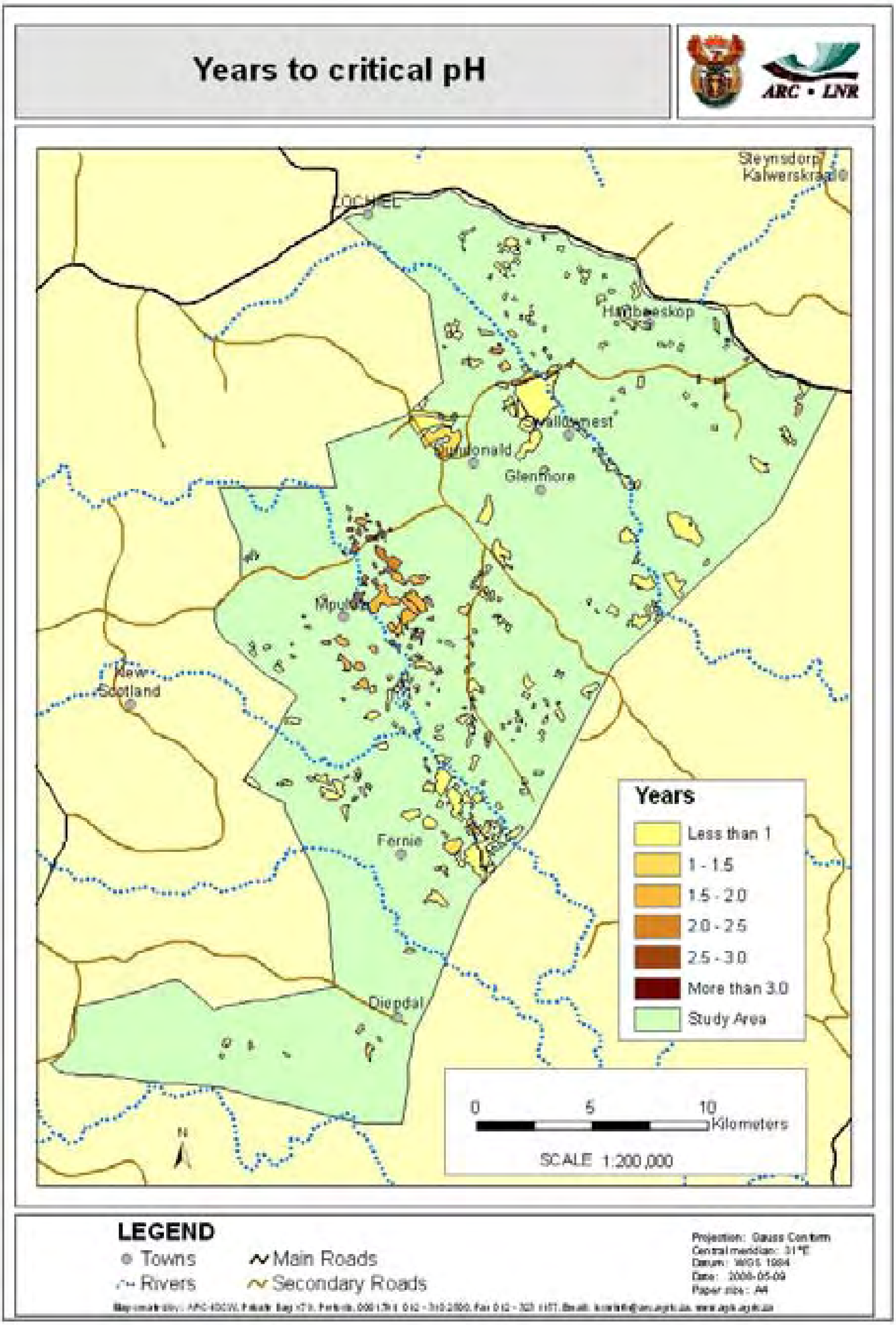
In order to spatially simulate the decline in soil pH (H_2O) of the topsoil (0-250 mm) over time, acid production loads were combined with geostatistics. Interpolated acidification risk maps were created at a 1:200 000 scale using pH (H_2O) change per annum (Δ pH unit year^{-1}), years until the critical pH (H_2O) of 5.68 is reached and a spatial risk classification of the district (Maps 7.10 to 7.12).

Map 7.10 indicates that the rate of pH decline for the top 250 mm soil depth was between 0.051 and 0.918 (mean 0.237) units year^{-1}, with the fastest rates on the crop production sites in the Mpuluzi and Fernie areas characterized by lower soil BC values. The acid generated from crop production practices (3.70 kmol (H^+) ha^{-1} year^{-1}) was sufficient to acidify the relatively weakly-buffered soil. Special care should be taken in the management of soils in this area because of the potential threat to sustainable agriculture due to the relatively high acidification rates. Cregan and Helyar (1990) suggested that the rate of acidification can be reduced by the adoption of more efficient and less acidifying agricultural practices. This includes the substitution of ammonium by nitrate fertilizers, improving the efficiency of nitrogen (*e.g.* apply NH_4^+ fertilizer when root system has developed) and water use (N-cycle), and minimizing waste product removal and excessive levels of organic matter (C-cycle).

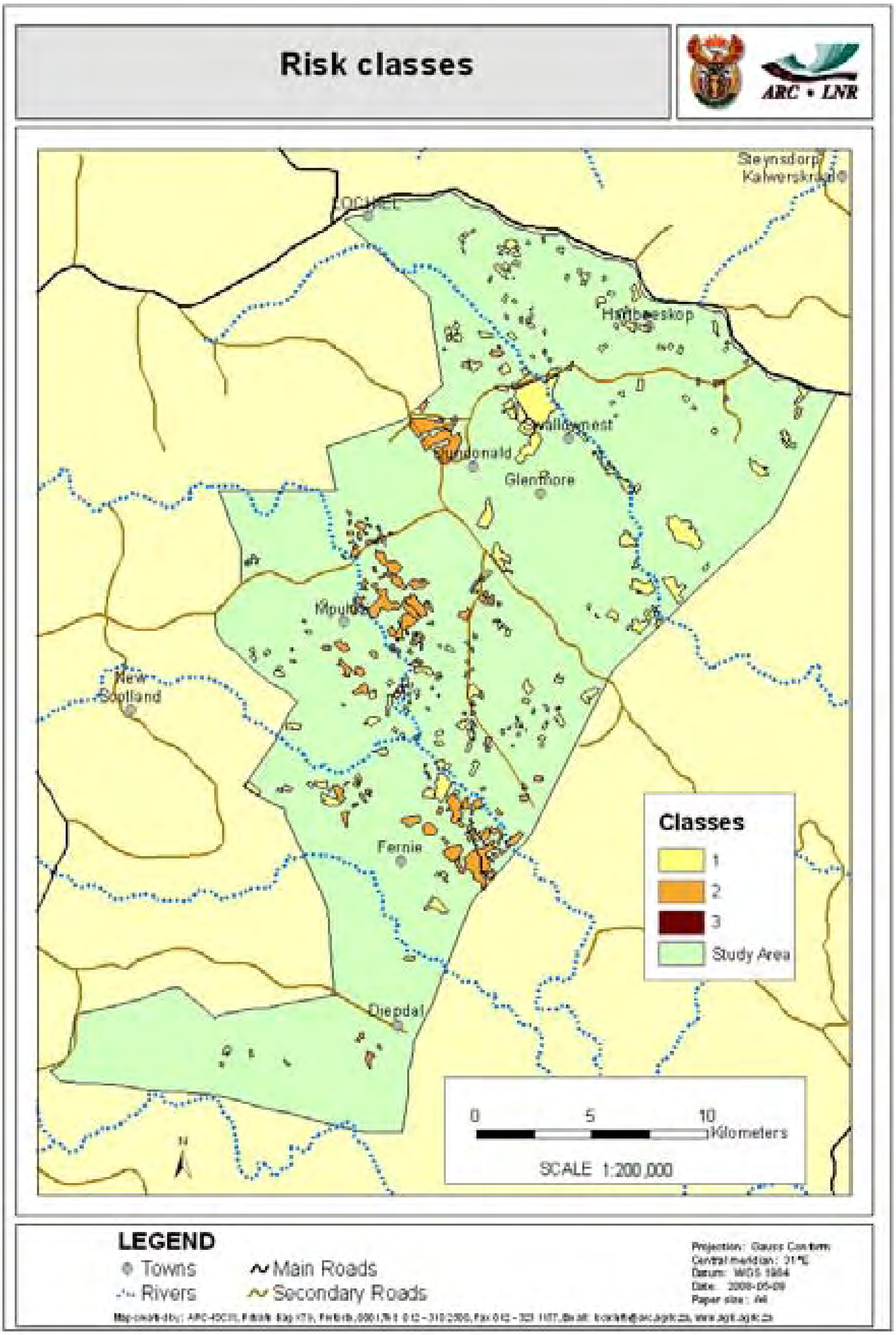
The expected number of years until a given critical pH is reached (Map 7.11) enables acidification risk predictions (Map 7.12) to be made by identifying the bracket within which the number of years falls (Hill, 2003). In the current study, class 1 indicates high-risk areas with pH values lower than critical pH values, class 2 indicates moderate-risk areas expected to acidify to critical pH in less than 5 years, and class 3 a low-risk area is not expected to acidify to critical pH within 5 years (Map 7.12).



Map 7.10 Interpolated map (1:200 000) of pH (H_2O) change per year for the topsoil (0-250 mm) in the Mlondozi district.



Map 7.11 Interpolated map (1:200 000) of years until critical pH (H_2O) is reached for the topsoil (0-250 mm) in the Mlondozi district.

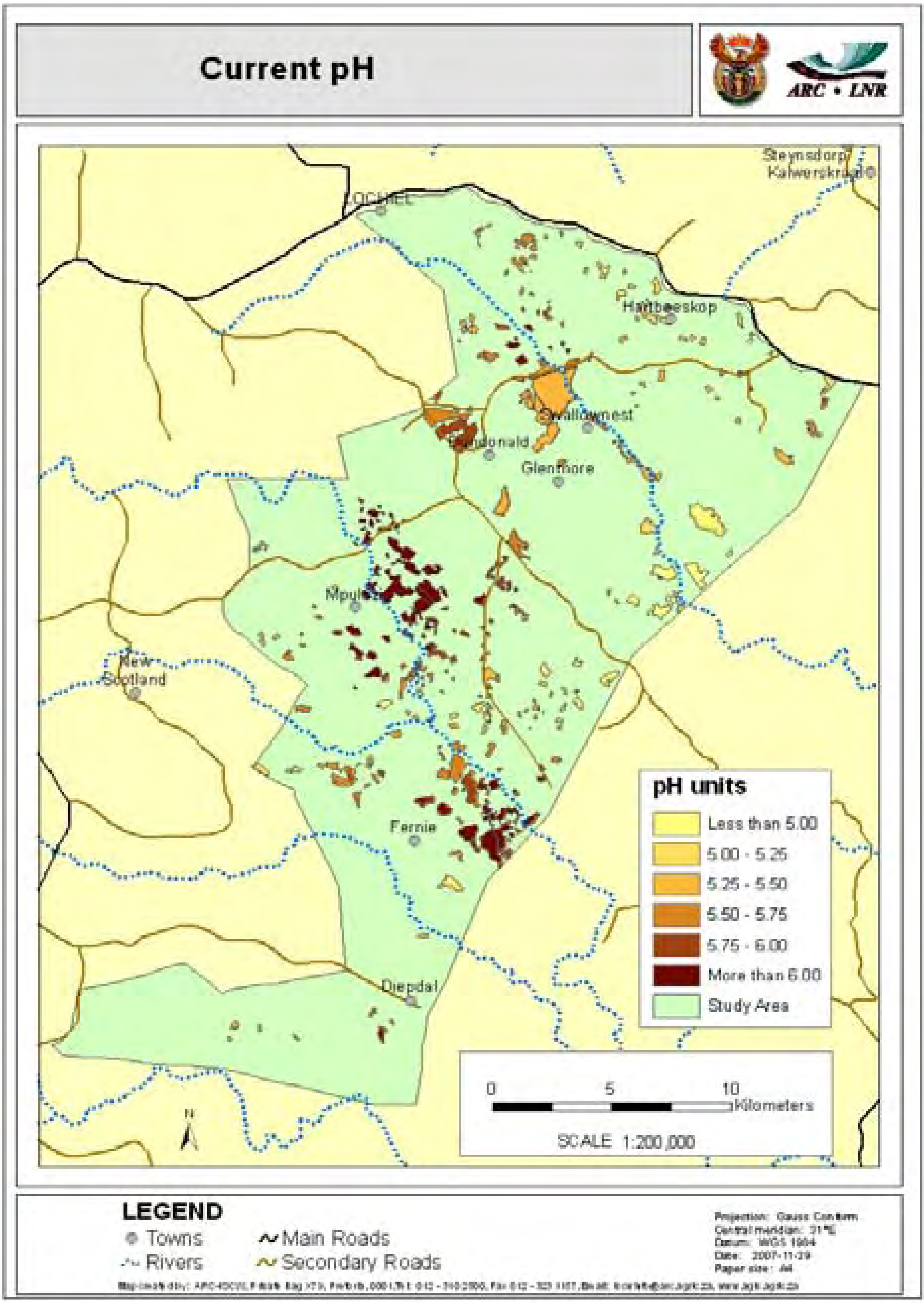


Map 7.12 Interpolated map (1:200 000) of risk classes for the topsoil (0-250 mm) in the Mlondozi district.

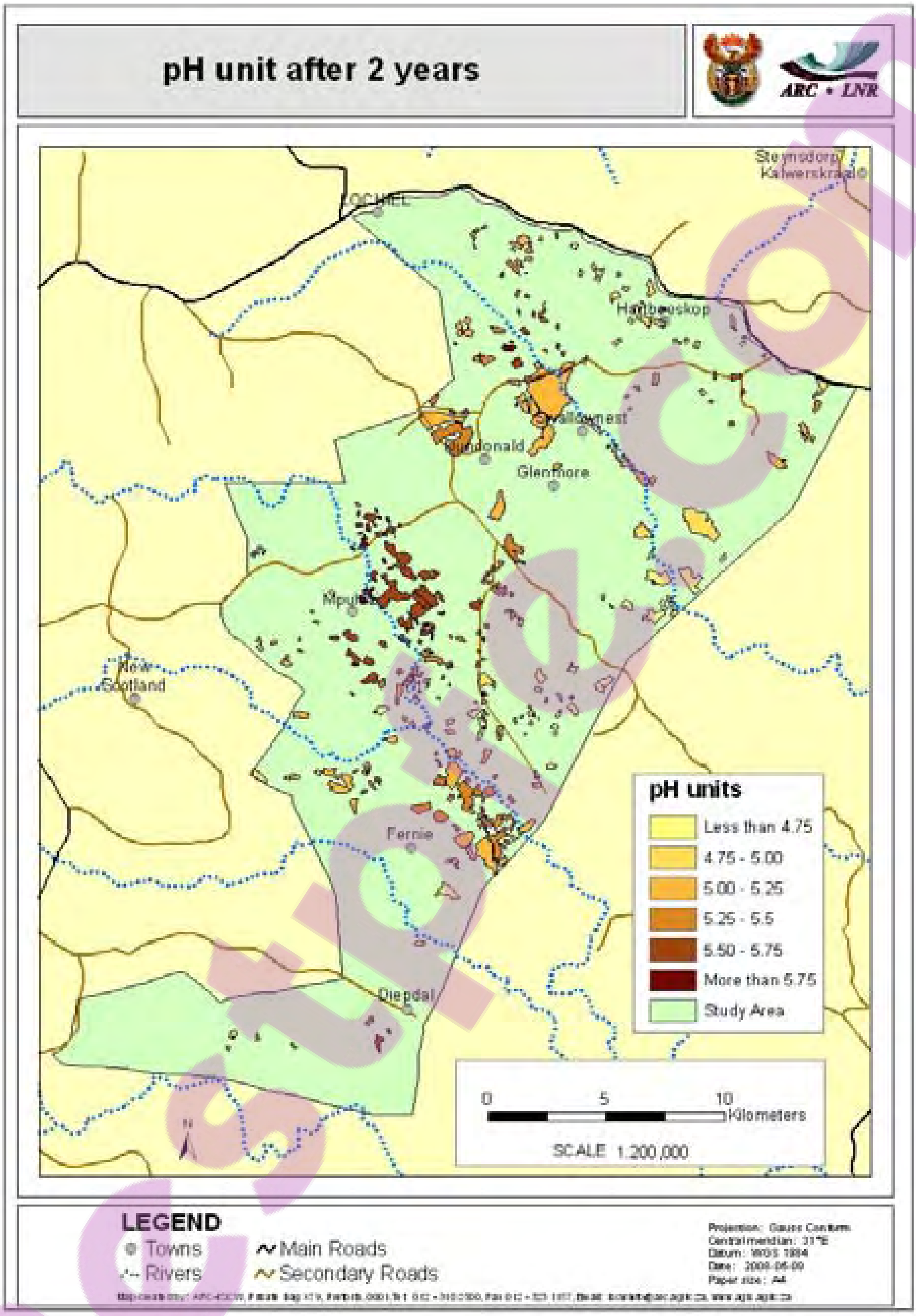
Maps 7.11 and 7.12 show that within two years the pH (H_2O) of most of the Mlondozi district would decrease to below the critical pH of 5.68. Results indicate that interventions should focus on cultivated areas in the central parts around Swallownest and Glenmore, the northern parts around Hartbeeskop, the eastern parts, and to the west and north of Fernie (risk class 1) where pH (H_2O) was already lower than the critical pH. Croplands in the areas around Dundonald, Mpuluzi, and north and east of Fernie fall within risk class 2, which indicates that the pH will decrease to below critical values within 5 years. The class 3 areas, with the lowest risk, constituted only very small areas around Mpuluzi and towards the north of Dundonald.

Maps 7.13 to 7.16 shows interpolated maps (1:200 000 scale) simulating pH (H_2O) values for a sequence of current, 2, 4 and 6 years. Compared with the current situation, a dramatic reduction in pH (H_2O) values could be expected within the relatively short period of 6 years. Generally the high risk areas as previously indicated are near the north-eastern border of the district, as well as the area around Fernie where pH (H_2O) values are predicted to decrease to less than 5.0 within 6 years. Results indicate that currently 50% of all cultivated lands have pH (H_2O) higher than critical values, but within 4 years this would decrease to 3% at an assumed APL of 3.70 kmol (H^+) ha^{-1} $year^{-1}$.

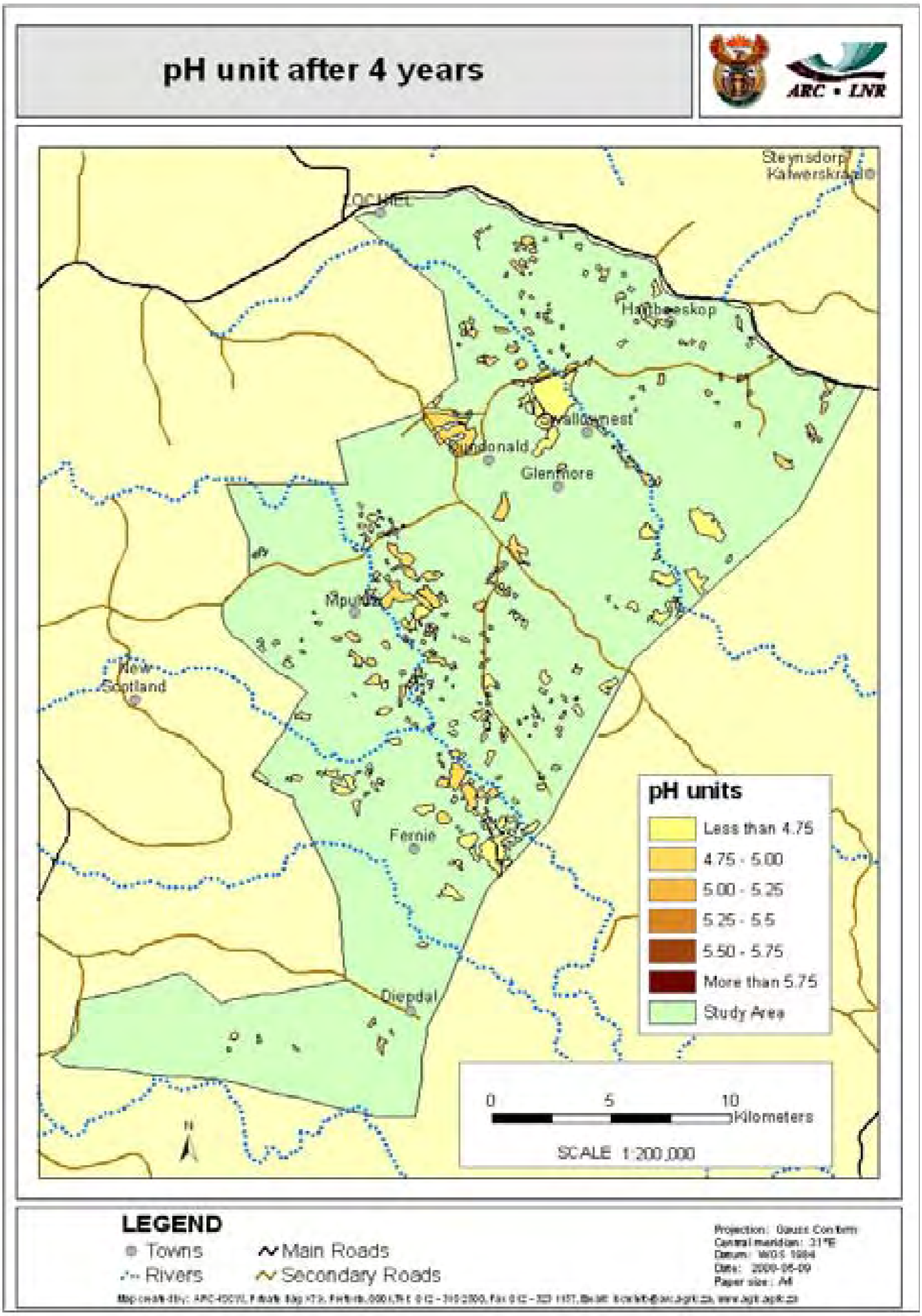
The above results highlight the risk of potential decrease in soil pH in the study area, which emphasize the need to re-examine present agricultural and intervention strategies in order to reduce the current soil acidification rates or consider subsidies for reliming.



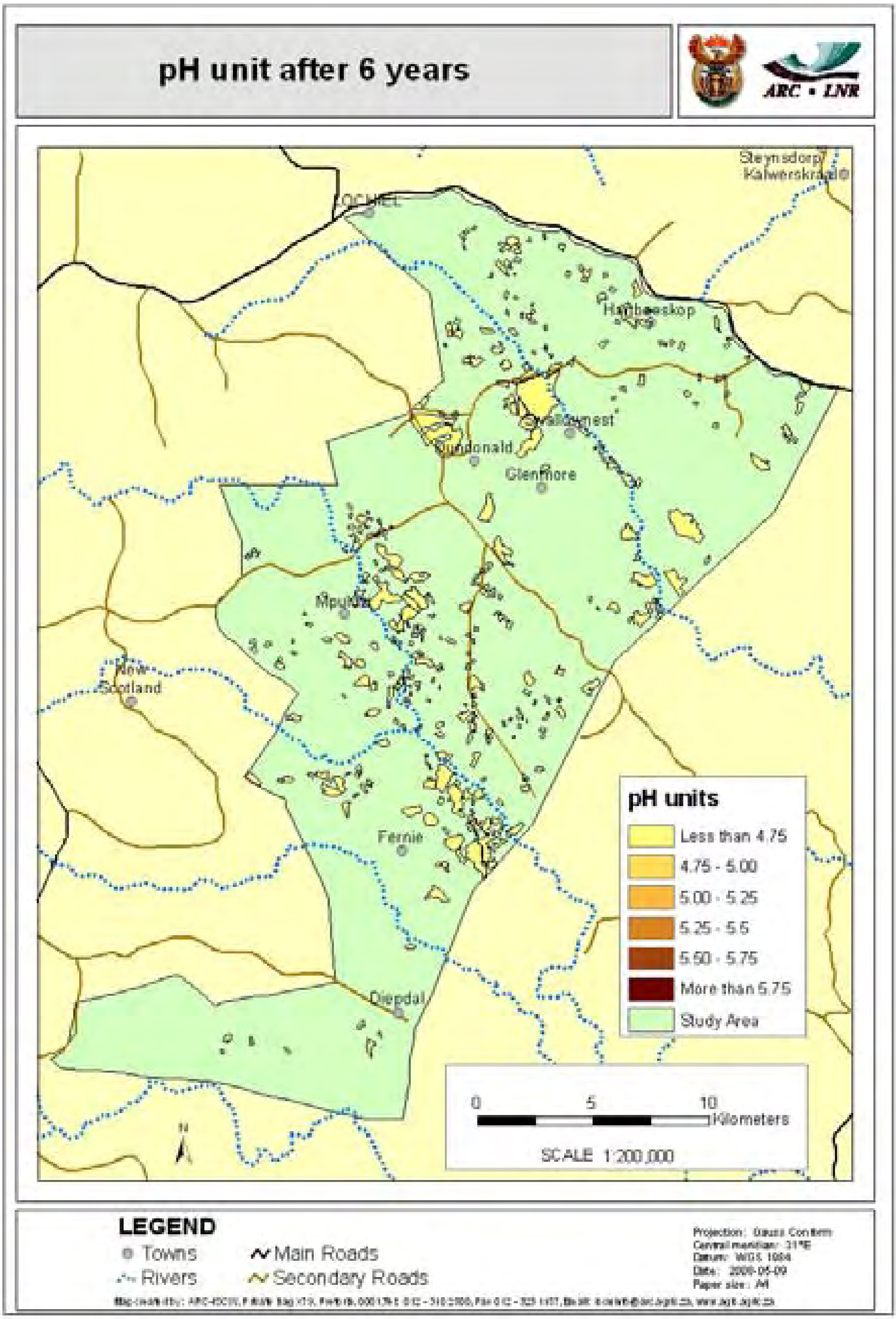
Map 7.13 Interpolated map (1:200 000) of simulating pH (H_2O) values for current pH for the topsoil (0-250 mm) in the Mlondozi district.



Map 7.14 Interpolated map (1:200 000) of simulating pH (H_2O) values for 2 years for the topsoil (0-250 mm) in the Mlondozi district.



Map 7.15 Interpolated map (1:200 000) of simulating pH (H_2O) values for 4 years for the topsoil (0-250 mm) in the Mlondozi district.



Map 7.16 Interpolated maps (1:200 000) of simulating pH (H_2O) values for 6 years for the topsoil (0-250 mm) in the Mlondozi district.

7.3.7 Relationship between acidification rate and selected soil properties

Table 7.3 shows that several soil properties were highly significantly ($P<0.001$) correlated with acidification rate. Soil pH (H_2O) and (KCl) are individually the best correlated ($r = 0.724, 0.628$) with acidification rate, followed by extractable Al and acidity (Al + H), clay content, acid saturation and ECEC. Table 7.3 and Figure 7.4 show that acidification rate (Δ pH unit year^{-1}) was high if the initial soil pH (H_2O or KCl) was high or extractable (Al + H), (Al) or acid saturation were low.

Doerge and Gardner (1985) stated that increased pH values which are the result of lime application, stimulate soil acidification processes and net soil acidification occurs at an accelerated rate. The reasons for the increase in acidification risk with increasing pH values are:

(i) The decomposition of organic matter is accelerated with an increase in pH. This leads to an increased release of reduced forms of N and S. The oxidation of these compounds would result in greater production of H^+ ions in limed soils. Marked increases in mineralized N were measured when liming raised the pH above 5.0 and 5.9, respectively. Increases in mineralization of organic S would also be expected (Doerge & Gardner, 1985).

(ii) It has been shown that extractable Al is a significant contributor to the pH buffer mechanism. At high pH values, extractable Al is essentially eliminated and other soil properties such as clay, organic C and CBD-Al, Fe are the primary buffering mechanisms (see Chapter 6).

(iii) Another reason for the greater net acid production load for soils with higher initial pH values shown by Gasser (1973), Hoyt and Henning (1982) and Matzner and Meiwes (1994) is that the rate of nitrification is influenced by the soil pH value. Nitrification, the process of enzymatic oxidation of ammonia to nitrates brought about by autotrophic microorganisms in the soil, proceeds most rapidly in soils with a higher pH value. This accounts in part for the weak nitrification in acid soils and the apparent sensitivity of the organism to a low pH (Brady, 1984). Therefore, acid production load in a soil with an initial low soil pH would be lower compared to the same soil with a higher pH value.

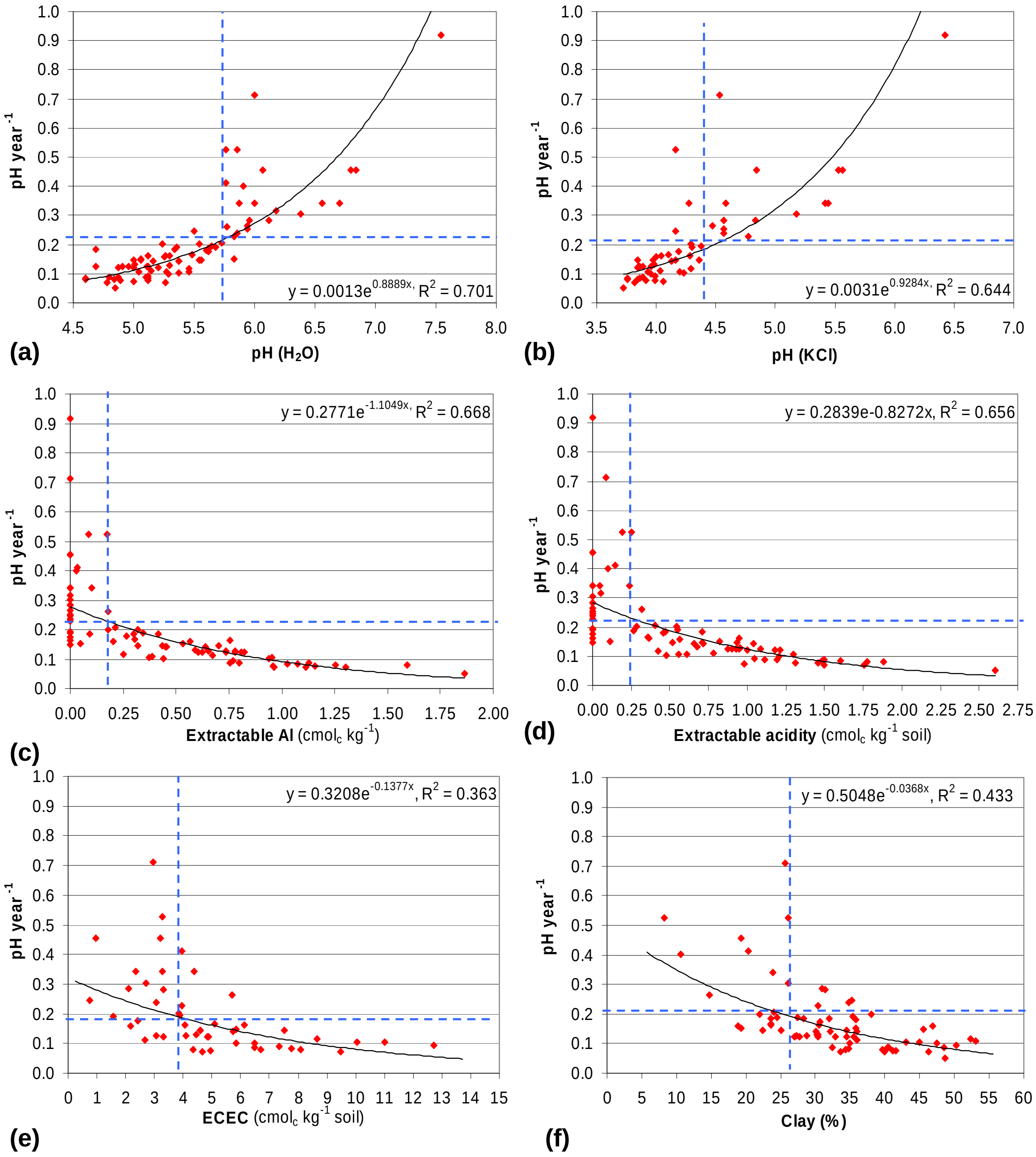


Figure 7.4 The relationship between acidification rate (Δ pH year^{-1}) and (a) soil pH (H_2O), (b) pH (KCl), (c) extractable Al, (d) extractable acidity, (e) ECEC (cmol$_c$ kg^{-1} soil) and (f) clay content.

Table 7.4 and Figure 7.4 show critical soil properties where acceleration in acidification could be expected.

Table 7.4 Non-linear regression analysis between various soil properties and acidification rate.

Variables	R^2 (%)	F	Critical value
Soil pH (H_2O)	57.72	102.39^{***}	5.73
Soil pH (KCl)	40.86	53.21^{***}	4.45
Extractable Al	47.48	69.60^{***}	0.180 $cmol_c$ kg $soil^{-1}$
Extractable acidity	47.92	70.84^{***}	0.253 $cmol_c$ kg $soil^{-1}$
ECEC	43.63	38.06^{***}	3.29 $cmol_c$ kg $soil^{-1}$
Clay	29.20	28.45^{***}	26.1%

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

Figure 7.4 (a) and Table 7.4 shows that above a critical pH (H_2O) value of 5.735, a gradual increase in acidification rates is accelerated. The pH (KCl) values show gradual accelerated acidification above 4.45 (Figure 7.4 (b)). This indicates that soils in the study area should, for economic reasons, not be limed to pH (H_2O) and (KCl) values higher than ≈ 5.75 and 4.45, respectively, due to accelerated acidification that would take place above these values. Critical threshold values for extractable Al and acidity were recorded as <0.180 and 0.253 $cmol_c$ kg^{-1} soil. Below these critical values acceleration in acidification could be expected (Figure 7.4 (c, d)). Figure 7.4 (e) shows that the acidification rate as affected by ECEC, the sum of extractable cations ($Al^{3+} + H^+ + Ca^{2+} + Mg^{2+} + K^+ + Na^+$), is the highest when the ECEC value drops below 3.29 $cmol_c$ kg^{-1} soil. Figure 7.4 (f) furthermore shows that, not surprisingly, the acidification risk decreased with an increase in clay content. The smallest change in pH value over time was recorded at a clay content higher than 26.1%. Therefore, soils with clay contents of <26.1% are at a greatest risk of accelerated acidification.

7.4 CONCLUSIONS

The farming community in the Mlondozi district has to make a living on soils where pH (H_2O) levels show that 40% of the topsoil has a pH below a critical value of 5.68, indicating that a decline in crop growth and yield may be expected. Average net acid production loads due to crop production (mainly maize) were calculated to be 3.70 H^+ ha^{-1} $year^{-1}$. The lime required to balance the net acid production load to 250 mm depth was between 97 and 527 kg $CaCO_3$ ha^{-1} $year^{-1}$, with a mean of 190 kg $CaCO_3$ ha^{-1} $year^{-1}$ in the crop production sites. The regular application of the small quantities of lime would be sufficient to maintain favourable pH levels. Other possibilities include non-acidifying fertilizers such as limestone ammonium nitrate, which may prevent further soil acidification.

The soil acidification risk techniques used in the study proved to be a valuable tool to assist land users, extension officers, and policy makers in making decisions on the long-term impact of production systems on the resource base. The results furthermore show the need to re-examine current agricultural and intervention strategies in order to reduce the impact of soil acidity and reduce current soil acidification rates. It has been shown in the study that the Mlondozi area (4 000 ha cropland) would require an amount of 760 tonnes $CaCO_3$ year^{-1} (based on the mean net acid production .load) to maintain current soil acidification rates in the Mlondozi district. From a strategic perspective, the quantification of acid production rates and the maintenance liming rate in the study area should assist producers, extension officers, and policy makers in making decisions towards preventing acidification and the long-term impact of a production system.

8

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The data and findings contained in this thesis reveal the benefits that can accrue by value-adding scientifically to empirical, multi-year field trials dealing with acid-soil infertility. They also demonstrate how findings can be extrapolated to adjacent croplands via soil chemical tests and spatial mapping of relevant soil fertility attributes. The two targeted 5-6 year maize (*Zea mays L*.) “extension” trials from a NLP liming initiative were located in resource-poor farming areas of Mpumalanga Province, South Africa, and each involved applications of from zero to 10 tonnes ha^{-1} of dolomite. Around 1500 resource poor farmers across ≈4000 ha of the Mlondozi District were covered by the subsequent extrapolation. A downside was the absence, in the field trials, of alternatives to dolomite as the “liming” source, despite knowledge that the $MgCO_3$ component of dolomite is measurably less reactive than its $CaCO_3$ component (Martin and Reeve 1955; McKeague and Sheldrick 1976). The consequence is that the $CaCO_3$ component of dolomite will have been responsible for the initial alleviation of soil acidification in the multiple-year field trials, followed subsequently by the $MgCO_3$ component. The 80 representative soil samples from the Mlondozi District equated to one sample for every 50 ha of cropping land, which is relatively low intensity but sufficient to demonstrate the value for technology-transfer purposes of spatial-mapping of targeted soil properties.

Collectively, the research program undertaken was sufficient to gain insight into the mechanisms that govern soil BC and the alleviation of soil acidification in the major cropping soils (Hutton and Oakleaf) of Mpumalanga Province, Herein, the implications of the results and their limitations are discussed, conclusions documented, and suggestions for future research outlined.

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

The typically recommended liming rate of 5 tonnes dolomite ha^{-1} successfully neutralized excessive soil acidity on the Hutton soil but not on the Oakleaf soil, which required a higher application rate (??? 10 tonnes dolomite ha^{-1}), attributable to its BC, which at around 2.49 cmol$_c$ kg^{-1} pH unit^{-1} was four-fold that measured in the surface horizon of the Hutton soil. Comparatively, Aitken *et al.* (1990)

reported soil pH BCs of Queensland (Australia) soils range from 02 to 5.4 g $CaCO_3$ kg^{-1} soil $unit^{-1}$ pH increase.

An explanation as to why the soil BCs should differ four-fold is open to speculation but a possible contributing factor may be that the A horizons of Oakleaf soils are closer to the zero point of charge than corresponding horizons of Hutton soils, noting that both soil types are dominated by 1:1 layer clays (see Table 2.1). Such clays are synonymous with strong weathering, low CECs and variably charged exchange sites (Theng 1980; Uehara and Gillman 1981). Other contributing factors could be differences in soil texture class (Murphy, undated) and the significantly higher levels of organic C in Oakleaf soils. Specifically, soil organic matter has a strongly pH-dependent charge that originates from, for example, the deprotonation of OH^- of active carboxyl (-COOH) and phenolic (C_6H_4OH) groups. These account for 85% of the negative charge of soil organic matter. Phenolic groups are weaker acids than carboxyl groups and contribute charge at higher pH, as compared to carboxyl. In the pH range of most soils (pH 4.5 - 8.0) carboxyl groups contribute negatively-charged surfaces that are strongly pH dependent.

Critical threshold values derived from pooled data were identified where reductions in relative grain yield occurred For pH (H_2O), extractable acidity, Al and acid saturation, these critical threshold values were 5.49, 0.277 $cmol_c$ kg $soil^{-1}$, 0.145 $cmol_c$ kg $soil^{-1}$ and 13%, respectively. Of these, acid saturation percentage is likely to be a useful indicator of the need for liming additions, since it aims at eliminating a major cause of poor growth within acid soils, i.e. toxic Al. As established by Bruce *et al.* (1999), however, soil ionic strength, which can be affected by inputs of chemical fertilizers, will affect the concentrations of active Al^{3+} in the soil solution and hence the level of Al saturation associated with Al toxicity. Clearly, further local research on the extent to which varying soil solution concentrations influence the expression of Al toxicity (or Ca^{2+} deficiency) would further improve the diagnosis of cause/s of acid-soil infertility.

8.2 To measure the effects of liming on growth and yield of maize:

The results of this study indicate that soil acidity has a confounding influence on soil fertility, leaf nutrient uptake and maize growth. The cause of poor crop growth is due to the associated chemistry that occurs at low pH, i.e. toxic levels of soluble Al plus lessened plant availability of P and Mo. Aluminium toxicity, excess Mn and possibly excess Fe, respectively, and deficient levels of Ca^{2+} (and possibly Mg^{2+}) were the factors that most adversely affected nutrient uptake and maize grain yields in the study area. The highest yields were associated with low leaf Al, Fe and Mn levels. It was also found that concentrations of total K and total B in maize leaves were lower in plants diagnosed as Al, Mn and Fe toxic. A previous study (Steyn and Herselman 2006) reported that trace elements such as B, Co, Cu, Fe, I, Mn, Mo, Se and Zn have a high risk of being deficient in this area. However, the current study showed that Zn, B and Mo fertilizer additions had little beneficial effect on maize growth. Farmers and extension personnel should be educated in the positive effects that these trace elements have on production and when positive responses might be expected.

8.3 To determine the relative importance of soil properties in determining the soil buffer capacity of the major soil groups:

With respect to the importance of soil properties in determining soil BC of 80 soil samples from the Mlondozi District, extractable acidity, organic C and clay content significantly contributed to pH buffering. However, limitations existed in interpreting the corresponding soil BC values because only limited information is available on this soil attribute for South African soils. The relative contributions soil properties to soil BC were derived via multiple regression analyses, where the significant independent variables were clay, organic C, extractable acidity, CBD-Fe & Mn, and pH and the dependent variables, soil BC at pH <4.5, 4.5-6.5, 6.5-8.5 & 4.5-8.5. The regression equations indicated that the mean relative contribution of extractable Al to soil BC in this group of soils varied from 69% at pH <4.5 to 80% at pH 4.5-8.5.

The current study clearly found considerable chemical and physical diversity in the dominant soils. Moreover, low pH, Al toxicity and relative high soil BC are likely contributors to poor maize growth on Magwa and Inanda soils. Fortunately, these constraints can be minimized by liming and by adequate rates of necessary fertilizer applications. The down-side is that due to the high soil BC values of these soils, applications of many tonnes ha^{-1} of liming material will be necessary to alleviate soil acidity. Although the Hutton and Clovelly soils currently have higher pH values, they will be more prone to soil acidification in the longer term than will the Magwa and Inanda soils due to the lower soil BCs of the former two soil types.

8.4 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:

The results of this research provide insights into the current maize production systems, soil acidification rates and management strategies. Topsoils affected by acidity span the entire study area. Previous studies by others found that rates of acidification can vary from 0.7 kmol H^{+} ha^{-1} year^{-1} in pristine systems to as high as 40 kmol H^{+} ha^{-1} year^{-1} in production systems receiving high rates of ammoniacal N fertilizers (Sumner & Noble, 2003).

A limitation existed in the current study in that general acid production estimates were used only to predict the effect of maize cultivation on acidification rates. Corresponding estimates could not be made for natural veld and forestry (*Pinus patula*), due to a lack of long term data for those locations. Furthermore, there is little South African data on the rate at which production systems acidify, as is available for locations and cropping systems in Australia (eg. Slattery *et al.* 1999). Investigation on the prediction of soil BC and lime requirement showed that these characteristics could successfully be predicted if soil properties such as extractable Al, organic C, clay content and pH (H_2O) were available. While the study showed the strong predictive value of these parameters, the validity in extrapolating the derived predictions beyond the study area is questionable.

The representation of spatial continuity of soil properties was done by depicting the surface continuously to show gradual variations in soil properties. Several approaches were investigated (e.g. kringing, spline function, etc.) before producing map surfaces by inverse distance weighting, as presented in this thesis. The limited number of data-points influenced the methodology employed. It is contended that the spatial “risk maps” are sufficiently accurate and informative to be use by regional extension officers and by farmers to identify areas that are already or are likely in the foreseeable future to become acidic, thus facilitating timely corrective measures by farmers seeking to ensure sustainable and profitable maize production systems. The average net acid production loads due to crop production (mainly maize) were calculated to be 3.70 H^+ ha^{-1} $year^{-1}$. The lime required to balance the net acid production load to 250 mm depth was between 97 and 527 kg $CaCO_3$ ha^{-1} $year^{-1}$, with a mean of 190 kg $CaCO_3$ ha^{-1} $year^{-1}$ in the crop production sites. This amounts to 760 tonnes $CaCO_3$ $year^{-1}$ for ≈ 4000 ha to maintain current soil acidification rates in the Mlondozi district. Caution should be taken in the interpretation of this data in that the amount of 190 kg $CaCO_3$ ha^{-1} $year^{-1}$ is only the maintenance liming requirement and not the lime requirement to bring soils to optimal pH (H_2O) values.

Future Research and Policy

While good progress has been made, all matters associated with acid soil infertility and soil acidification rates have not been resolved by the study. In future studies, the evaluation of the acid production load of different production systems in resource poor farming communities may be useful. Moody and Aitken (1997), and Dolling & Porter (1994) aimed to calculate acidification rates if several agricultural systems in tropical subtropical Queensland. A similar approach is warranted for South African crop, pasture and forestry production systems.

Currently, only limited information is available on soil BCs across South Africa despite the highly weathered nature of most soils and the widespread occurrence of acidic soils. It follows that nation-wide studies to reliably assess lime requirements is warranted, preferably based on soil testing methods already available from soil testing services in the country. This would enable land users to make more informed decisions on lime requirement at paddock scale.

The results obtained and lessons learned in the study serve as a guide to similar projects in resource-poor farming areas in South Africa. There is a need to re-examine current agricultural and intervention strategies in order to reduce the impact of soil acidity and reduce current soil acidification rates. Also, to ensure the sustainability of similar projects, policy makers should ensure service infrastructures are in place so as land users have reliable access to lime, fertilizer, seed and necessary agricultural machinery. In addition, policy makers should have access to detailed knowledge or descriptions of local soils (e.g. soil maps), in addition to good advice on lime and nutrient requirements on a locality and soil-type basis. Risk areas should be delineated to ensure priority is given to areas and farmers most in need of these inputs. Long-term action plans should be developed for liming and fertilization operations, for annual extension programmes and for off-load sites for lime or dolomite. Planning at this level of detail and scale will help to enable the resource poor farming sector to produce to its full potential, which represents a relatively untapped source of agricultural production potential.

Conclusions

Conclusions from this study are documented in accord with five main objectives.

Objective 1: *Monitoring the effects of liming on the neutralization of soil acidity and determining the re-acidification rate of soils under cultivation.*

The recommended level of 5 tonnes lime (as dolomite) ha^{-1} increased soil pH (H_2O) to above 5.5 within one year of application and thereafter on Hutton soil.

The longevity of liming (5 and 10 tonnes dolomite ha^{-1}) on surface soil pH (H_2O), relative to unlimed soil, extended for at least the 6 years at the trial sites studied.

Within the first season after lime application, the majority of extractable acidity was displaced even though the soil pH (H_2O) showed a lag period of 2 to 3 years after liming.

The Oakleaf soil, with its relatively high soil BC, showed the greatest resistance to change and larger amounts of lime needed to be applied to bring about a desirable change in soil acidity in this soil compared to the Hutton soil.

The critical thresholds when a reduction in relative yield was recorded were pH (H_2O) = 5.49, extractable acidity (Al + H) = 0.28, extractable acidity Al = 0.15 cmol$_c$ kg soil^{-1} and acid saturation =13%.

Soil BC decreased over time in the Hutton soil, while no significant reduction in soil BC was measured in the Oakleaf soil.

Organic C, extractable acidity and Al were strongly positively correlated with soil BC in the Hutton soil. A significant reduction in extractable acidity with dolomite applications was recorded in the Hutton soil and it is therefore postulated that the neutralization of extractable acidity due to liming resulted in a reduction in soil BC.

Acid production loads varied quite dramatically in both experimental soils with values ranging from 1.61 to 8.82 kmol H^+ ha^{-1} $year^{-1}$ with the highest values observed in the dolomite treatments on the Oakleaf soil.

The soil BC determined from the pH (H_2O) range 4.2 to 8.5 ($BC_{(4.2\text{-}8.5)}$), was the most appropriate in the prediction of measured acidification rates in both experimental soils.

The pH (H_2O) acidification rate for the unlimed treatment at initial pH (H_2O) of 5.33 acidified by -0.046, while the 10 tonnes lime treatment at a maximum pH (H_2O) of 6.47 acidified by -0.140 pH (H_2O) unit $year^{-1}$ for the Hutton soil. The pH (H_2O) acidification rates for the Oakleaf soil varied from -0.044 for the unlimed plot at an initial pH (H_2O) of 4.54 to -0.110 pH (H_2O) unit $year^{-1}$ for the 10 tonnes lime rate at an initial pH (H_2O) of 5.15.

At a pH (H_2O) of 4.10 and 3.95 an acidification rate of zero could be expected in the Hutton and Oakleaf soils, respectively.

The maintenance liming rate (as dolomite) of the topsoil (0-250 mm) of the Hutton soil form ranged from 1.4 tonnes $CaCO_3$ ha^{-1} $year^{-1}$ for a pH (H_2O) of about 6.5 (10 tonnes dolomite ha^{-1} level), to 0.2 tonnes $CaCO_3$ ha^{-1} $year^{-1}$ for an attained pH (H_2O) of about 5. The maintenance lime requirement for the Oakleaf soil ranged from zero at an average pH (H_2O) of 4.3 that was attained over 5 years, to 0.8 tonnes $CaCO_3^{-1}$ ha^{-1} $year^{-1}$ in the 5 and 10 tonnes dolomite ha^{-1} levels.

Objective 2: Effects of liming on growth and yield of maize.

The accumulated results over five and six seasons show a significant improvement in soil fertility status with liming in terms of increases in extractable soil Ca, Mg, Cu, Zn and Mo levels in the Hutton soil. This resulted in improved uptake of N, P, Ca and Mg by maize as was manifested in maize leaf nutrient concentrations. Dolomite application, furthermore, improved the availability of soil Ca, Mg and Mo, and plant uptake of Ca and Mg in the Oakleaf soil.

Critical soil nutrient concentrations were determined from fitted relationships between soil nutrient concentrations and relative yield. Under the experimental conditions, soil nutrient levels of 50 mg kg^{-1} K, 228-345 mg kg^{-1} Ca, 78-105 mg kg^{-1} Mg and 1.68-2.85 mg kg^{-1} Cu were calculated. The critical levels for soil Ca, Mg and Cu were higher than critical values reported elsewhere in South Africa, while soil extractable K was below the adequate range reported in local literature.

Interrelationships between maize yield, soil and plant nutrients showed a strong relationship between soil P and Mo in the Hutton soil, with improved absorption of Mo with increasing concentrations of total plant P.

Improved N uptake, through dolomite and fertilizer application, stimulated leaf P uptake in both experimental soils.

High soil Al levels were accompanied by relatively low soil Ca, Mg and leaf Mg concentrations in the Oakleaf soil.

Maize yield in the Hutton soil was adversely affected by Al-toxicity. Multiple regressions showed that leaf Fe, Ca, Zn and Mg accounted for 56.2% of the variation in maize grain yield in the Hutton soil. Leaf Ca was found to be the most important factor determining maize grain yield, followed by toxic soil Al and a depressed leaf B uptake in the Oakleaf soil. From this it is possible that soil Ca deficiency may be at least as important as Al toxicity, an observation already identified by Bruce *et al* (1989).

Nutrient vector analyses showed a toxic build-up of Fe, followed by Al, and to a lesser extent by Mn. The toxic elements depressed the uptake of Ca and Mg in the Hutton soil. In the Oakleaf soil, Al toxicity, followed by high levels of Mn and Fe markedly reduced the uptake of Ca and Mg. Antagonistically reduced B uptake due to Fe, Mn and Al toxicity was observed in the Hutton soil. Toxic levels of Al, Mn and Fe antagonistically depressed the uptake of K in the Oakleaf soil.

Aluminium, Mn and Fe toxicity, and deficient levels of Ca and Mg were the factors most adversely affecting nutrient uptake and maize grain yields in the study areas. Highest yields were associated with low leaf Al, Fe and Mn levels. It was also found that the uptake of leaf K and B decreased measurably under severe Al, Mn and Fe toxicity.

Objective 3: Relative importance of soil properties in determining the soil buffer capacity (BC) of the major soil groups.

Typical soil BCs over the general pH range 4.5 to 8.5 varied from 0.12 to 2.23 cmol$_c$ kg^{-1} pH unit^{-1} for 80 acidic topsoils in the Mlondozi District study area. Composite titration curves for dominant soil forms exhibited a wide range of buffering to base (OH^-) addition. Inanda soils showed a tendency of good buffering, while Clovelly soils revealed poor buffering. Maximum buffering for the experimental soils occurred at both pH <5.5 and >7.5, with general poor buffering between pH 5.25 to 7.5.

Linear regression analysis showed that the study area's soil BC values are determined primarily by three soil properties, *viz.* organic C content, content of clay minerals, and the type of clay minerals. Since the primary clay mineral in Mlondozi District is kaolinite with low soil BC, the clay content rather that the type of clay was the primary local determinant of soil BC.

Multiple regression showed that extractable Al significantly contributed to soil BC in the pH ranges <4.5 and 4.5-6.5, accounting for 69 and 75%, respectively, of the variation in soil BC$_{<4.5}$ and soil BC$_{(4.5\text{-}6.5)}$. Statistical analyses of the data from this study indicated that clay content, organic C, pH (H_2O), CBD-Mn, and Ca contributed most to the prediction of the soil BC$_{(6.5\text{-}8.5)}$.

Principal component analysis showed that high clay content soils were associated with relatively high CEC, CBD-Fe and CBD-Mn values in the study area. Low extractable Al was associated with low soil BC, acid saturation and high pH, Ca and Mg values.

Principal component analysis, furthermore, showed that Clovelly and Hutton soils tended to have lower soil BC, extractable acidity, Al and acid saturation values, and higher pH, Ca and Mg contents. Magwa and Inanda soils had higher soil BC, extractable Al (acidity) and acid saturation, and lower pH, Ca and Mg values. Therefore, more dolomite would be required to neutralize soil acidity in the more strongly buffered Magwa and Inanda soils as compared to the Clovelly and Hutton soils with lower soil BC.

The current knowledge of the soils in the study area indicates that there is considerable diversity across the dominant soils. Poor crop growth on Magwa and Inanda soils could be expected due to low pH and Al toxicity (or Ca^{2+} deficiency). Unfortunately, due to the high soil BC values of these soils, lime (or dolomite) rates upwards of 10 tonnes ha^{-1} would be necessary to alleviate soil acidity. However, the Hutton and Clovelly soils will be more prone to soil acidification than the Magwa and Inanda soils due to the lower soil BC's of the former.

Objective 4: *Mechanism that governs soil acidification, estimating soil acidification rates of the major soil groups, making recommendations and setting guidelines for efficient lime application rates to ensure sustainable land use*

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Average net acid production loads due to crop production (mainly maize) were calculated to be 3.70 kmol H^+ ha^{-1} $year^{-1}$. The lime requirement to balance the net acid production load to 250 mm depth was between 97 and 527 kg $CaCO_3$ ha^{-1} $year^{-1}$, with a mean of 190 kg $CaCO_3$ ha^{-1} $year^{-1}$ for the cultivated sites.

Interpolated acidification risk maps showed that a decline in pH (H_2O) of between 0.051 and 0.918 (mean 0.237) units $year^{-1}$ was recorded, with the fastest rates on the cultivated sites in the Mpuluzi and Fernie areas. Timely corrective measures should be taken by farmers in these areas in view of the potential threat to sustainable agriculture due to high acidification rates.

Temporal simulation of time until the critical pH is reached showed that within two years the pH (H_2O) of most of the district would decrease to below 5.7. Cultivated areas in the central parts around Swallowsnest and Glenmore, the northern parts around Hartbeeskop, the eastern parts, and to the west and north of Fernie fall within risk class 1, indicating that pH (H_2O) was already below the derived critical value. Croplands in the areas around Dundonald, Mpuluzi, and north and east of Fernie fall within the risk class 2, which indicates that the pH (H_2O) will decrease to below the derived critical value within 5 years. The class 3 areas around Mpuluzi and towards the north of Dundonald had the lowest risk, and are not expected to acidify to the critical soil pH within 5 years.

Interpolated maps simulating pH (H_2O) values for a sequence of 2, 4 and 6 years showed a dramatic reduction in pH (H_2O) values within 6 years. Currently 50% of all cultivated lands have a pH (H_2O) higher than critical values, but within 4 years this would likely decrease to 3% at an assumed APL of 3.70 kmol (H^+) ha^{-1} $year^{-1}$.

Higher soil acidification risks exist if the initial soil pH value was high or the extractable acidity (Al + H) or Al was low. It is recommended that the soils in Mlondozi be limed to a pH (H_2O) value of around 5.7, because below 5.7 a loss in crop production can be expected, and above pH (H_2O) 5.7 gradual acceleration in soil acidification takes place.

From a management perspective, soils with high initial pH values, low extractable Al and acidity values of below 0.18 and 0.25, respectively, clay contents below 26%, and a ECEC value below 3.29 $cmol_c$ kg^{-1}, are more prone to acidification than soils with a lower initial pH, higher extractable Al and acidity values, clay content above 26% and an ECEC value of 3.29 $cmol_c$ kg^{-1} and higher.

Specific Recommendations

The following recommendations are intended to assist in the process of implementing liming intervention strategies based on results from this study:

A risk exists in estimating when lime will again be needed based on a single soil sampling event. It is therefore recommended that extractable acidity is monitored annually, or every other year, in conjunction with soil pH to assist in the management of on-farm soil acidity in the Mlondozi district. Moreover, when making average or median soil pH calculations, the measured pH values should first be converted into –log [H^+] before applying the relevant mathematics. The resultants must then be transformed back to pH units (antilog).

The present study has furthermore shown the importance of implementing conservative agricultural practices to maintain organic C levels in order to avoid the immense release of H^+ and Al^{3+} acidity. From the results it is recommended that a conservation agriculture approach, including *inter alia* reduced or no-tillage and crop rotations, be further investigated and subsequently strongly recommended under resource-poor farming conditions.

Continuous maize cultivation and inappropriate nitrogenous fertilization have the potential to generate sufficient acidity that crop production (e.g. maize, legumes etc.) might have to be abandoned due to Al and Mn toxicity in many agricultural lands in the Mlondozi district. It is therefore recommended that land management practices designed to stall or reduce soil acidification be adopted as soon as possible.

Critical values, as reported in this study, are not infallible but can serve as a guide in the interpretation of the problems associated with soil acidity. It is recommended that the critical levels reported be used to assist in identifying nutrition deficiencies and imbalances responsible for yield depression, which could assist in the implementation of useful and sound cultivation and cropping practices.

The current knowledge of the soils in the study area indicates that there is considerable diversity in the dominant soils. It is estimated that the more strongly buffered Magwa and Inanda soils would require more lime to neutralize soil acidity as compared to the Clovelly and Hutton soils with lower soil BC. Poor crop growth on Magwa and Inanda soils could be expected due to low pH and Al toxicity. It is a well-known fact that liming and adequate rates of fertilizer application are the most effective management strategies to overcome acidity and soil fertility constraints to crop production. Unfortunately, due to the high soil BC values of these soils, liming rates upwards of 10 tonnes ha^{-1} will often be necessary to alleviate soil acidity. However, the Hutton and Clovelly soils will be more prone to soil acidification than the Magwa and Inanda soils due to the lower soil BCs of the former. This stresses the importance of implementing sound management strategies on especially Hutton and Clovelly soils due to their vulnerability to soil acidification. Regular maintenance applications of lime or dolomite will be required, while applications of non-acidifying fertilizers such as limestone ammonium nitrate, will help lessen further soil acidification, if their high cost can be justified.

The soil acidification risk techniques and spatial maps as a component of technology transfer used in the study, is a valuable tool to assist land users, extension officers, and policy makers in making decisions on the long-term impact of production systems on the resource base. It is therefore recommended that similar studies should be performed whenever government intervention strategies are implemented in resource-poor farming areas in order to identify risk areas.

A greater emphasis needs to be placed on current agricultural and intervention strategies in order to reduce the impact of soil acidity and reduce current soil acidification rates.

Leading farmers (local leadership) can play a very important role in the long-term sustainability of intervention strategies and should receive continuous training, capacity building and support (e.g. follow-up refresher courses).

A greater emphasis needs to be placed on positively changing the behaviour and practices of primary intended users. Strategies such as farmer-to-farmer extension, together with other strategies such as look-and-learn visits, farmer group dynamics and farmer co-operatives, could result in a much wider impact (out-scaling) and must be promoted. This should lead to accelerated adoption of conservation agriculture practices.

Finally, the efficacy of different forms of local liming materials needs to be assessed, noting that dolomite has limitations due to the variable release of its Ca and Mg components. Liming materials containing soluble silicates should be included in such studies, as highly weathered soils are often acidic and low in soluble silicates.

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