

**Soil chemical and nutrient uptake dynamics of maize
(*Zea mays* L.) as affected by neutralization and re-acidification after
liming**

by

Hester Getruida Jansen van Rensburg

Thesis submitted in partial fulfillment of the requirements for the degree Doctor of Philosophy
in Soil Science
in the
Faculty of Natural and Agricultural Sciences
University of Pretoria
Pretoria

October 2009

Supervisor: Prof A S Claassens
Co-Supervisor: Dr D J Beukes



Declaration

I, the undersigned, hereby declare that the work contained in this thesis is entirely my own original research, except where acknowledged, and that it has not at anytime, either partly or fully, been submitted to any University for the purposes of obtaining a degree.

Signed: _____

Date: _____

TABLE OF CONTENT

ABSTRACT	viii
CHAPTER 1: INTRODUCTION.....	1
1.1 BACKGROUND	1
1.2 JUSTIFICATION	1
1.3 SOUTH AFRICAN LANDCARE PROGRAMME	2
1.3.1 Goal of the national Landcare programme	2
1.3.2 National Landcare principles.....	3
1.3.3 Purpose of the South African Landcare programme	3
1.4 THE MLONDOZI LANDCARE PROJECT	4
1.5 PROJECT OBJECTIVES	6
1.6 STUDY AREA	7
1.6.1 Locality and physical features.....	7
1.6.2 Climate.....	9
1.6.3 Geology and soils	9
1.6.4 Vegetation.....	12
1.6.5 Land use	12
1.6.6 Demographic information.....	12
1.7 GENERAL STRUCTURE OF THE THESIS	13
CHAPTER 2: AN EVALUATION OF LIME EFFECTS ON TEMPORAL CHANGES IN SOIL ACIDITY PROPERTIES AND MAIZE GRAIN YIELDS	14
2.1 INTRODUCTION	14
2.2 MATERIAL AND METHODS	15
2.2.1 Soils and experimental design	15
2.2.2 Soils sampling and analysis.....	16
2.2.3 Planting and yield estimates	17
2.2.4 Rainfall data.....	17
2.2.5 Statistical analysis	18
2.3 RESULTS AND DISCUSSIONS	19
2.3.1 Soil pH, extractable acidity, Al and acid saturation	19
2.3.2 Grain yield versus lime application	21
2.3.3 Absolute grain yield versus soil acidity properties.....	23
2.3.4 Relative grain yield versus soil acidity properties.....	24
2.4 CONCLUSIONS	25
CHAPTER 3: THE EFFECT OF LIMING ON SOIL BUFFER CAPACITY, ACIDIFICATION RATES AND MAINTENANCE LIMING	27
3.1 INTRODUCTION	27



3.2	MATERIALS AND METHODS	28
3.2.1	Experimental soils.....	28
3.2.2	Soil sampling and analysis.....	28
3.2.3	Soil buffer capacity (soil BC).....	28
3.2.4	Acid production loads (APL) and acidification rates.....	29
3.2.5	Maintenance liming.....	30
3.2.6	Statistical analysis	30
3.3	RESULTS AND DISCUSSION.....	31
3.3.1	Effect of lime application on soil BC.....	31
3.3.2	Acid production loads	33
3.3.3	Soil BC vs soil acidification rate.....	34
3.3.4	Effect of lime application on soil acidification rates	44
3.3.5	Lime loss and maintenance lime rate	40
3.4	CONCLUSIONS.....	44
CHAPTER 4: LIMING EFFECTS OF SOIL PROPERTIES, NUTRIENT AVAILABILITY AND GROWTH OF MAIZE		45
4.1	INTRODUCTION	45
4.2	MATERIAL AND METHODS.....	46
4.2.1	Experimental layout and procedure	46
4.2.2	Soil and leaf sampling and analysis.....	46
4.2.3	Statistical analysis and data interpretation.....	47
4.3	RESULTS AND DISCUSSION.....	48
4.3.1	Effect of liming on soil and leaf nutrient availability.....	48
4.3.2	Critical soil nutrient concentrations and yield	61
4.4	CONCLUSIONS.....	53
CHAPTER 5: EFFECT OF SOIL ACIDITY AMELIORATION ON MAIZE YIELD AND NUTRIENT INTERRELATIONSHIPS IN SOIL AND PLANTS USING STEPWISE REGRESSION AND NUTRIENT VECTOR ANALYSIS.....		54
5.1	INTRODUCTION	54
5.2	MATERIAL AND METHODS.....	55
5.2.1	Experimental procedure.....	55
5.2.2	Soil and maize plant sampling and analysis	55
5.2.3	Statistical analysis and data interpretation.....	56
5.2	RESULTS AND DISCUSSIONS	57
5.3.1	Interrelationship between maize grain yield, soil and leaf nutrients	57
5.3.2	Nutrient uptake interactions	61
5.3	CONCLUSIONS.....	63
CHAPTER 6: RELATIONSHIPS BETWEEN SOIL BUFFER CAPACITY AND SELECTED SOIL		



PROPERTIES.....	65
6.1 INTRODUCTION	65
6.2 MATERIAL AND METHODS.....	66
6.2.1 Soils.....	66
6.2.2 Soil analysis.....	66
6.2.3 Potentiometric titration curves.....	67
6.2.4 X-ray diffraction analysis.....	67
6.2.5 Statistical analysis	67
6.3 RESULTS AND DISCUSSION.....	68
6.3.1 Soil characteristics.....	68
6.3.2 Potentiometric titration curves.....	69
6.3.3 Soil buffer capacity over limited pH ranges vs soil properties	70
6.3.4 Interrelationships between soil properties contributing to soil buffer capacity.....	74
6.3.5 Relationship between dominant soil forms and selected soil properties	77
6.4 CONCLUSIONS.....	78
CHAPTER 7: ASSESSING THE POTENTIAL SOIL ACIDIFICATION RISK UNDER DRYLAND AGRICULTURE	80
7.1 INTRODUCTION	80
7.2 MATERIAL AND METHODS.....	81
7.2.1 Study area	81
7.2.2 Soil sampling and analysis.....	83
7.2.3 Soil buffer capacity (BC)	83
7.2.4 Acid production loads (APL), acidification rates and maintenance liming.....	84
7.2.5 Spatial interpolation of soil properties and acidification risk.....	84
7.2.6 Statistical analysis	85
7.3 RESULTS AND DISCUSSION.....	85
7.3.1 General and spatial soil characteristics	85
7.3.2 Soil buffer capacity (BC)	86
7.3.3 Critical soil acidity indices	92
7.3.4 Actual soil acidity indices and lime requirement (LR).....	93
7.3.5 Acid production load (APL)	101
7.3.6 Acidification risk assessment.....	101
7.3.7 Relationship between acidification rate and selected soil properties	111
7.4 CONCLUSIONS.....	113
CHAPTER 8: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.....	115
REFERENCES.....	125
ACKNOWLEDGEMENTS	133

TABLE OF TABLES

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)	10
Table 2.1	Selected soil physical and chemical properties of the topsoil (0-250 mm) of the two experimental sites prior to establishment of trials	16
Table 2.2	Quality analysis values by calcium carbonate equivalent and resin suspension method of the experimental lime	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).....	18
Table 2.4	ANOVA table of probabilities of treatment effects on soil pH (H ₂ O), extractable (H+Al), Al, acid saturation, organic C and maize grain yield for the Hutton and Oakleaf soil forms	18
Table 2.5	Changes in soil pH (H ₂ O), extractable acidity, Al and acid saturation as affected by lime (tonnes ha ⁻¹) in the Hutton and Oakleaf soil forms over time	20
Table 2.6	Changes in absolute maize grain yield as affected by lime (tonnes ha ⁻¹) in the Hutton and Oakleaf soil forms over time	22
Table 2.7	Pearson's coefficients of correlation (r) between different variants for the Hutton and Oakleaf soil forms	22
Table 2.8	Non-linear regression analysis between absolute yield and soil acidity properties for pooled data for the Hutton and Oakleaf soil forms	23
Table 2.9	Non-linear regression analysis between relative yield and soil acidity properties for pooled data for the Hutton and Oakleaf soil forms	24
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	31
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	32
Table 3.3	Pearson's coefficient of correlation (r) between soil BC, organic C and extractable acidity for the Hutton and Oakleaf soil soils	33
Table 3.4	Acid production loads and acidification rates for the topsoil (0-250 mm) of the Hutton and Oakleaf soil forms as a function of liming	33
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	41
Table 3.6	Maintenance lime requirement rates in the topsoil (0-250 mm) of the Hutton and Oakleaf soil forms as a function of liming	43
Table 4.1	Selected soil chemical topsoil (0-250 mm) properties ¹ of the experimental sites.....	

.....	46
Table 4.2	ANOVA table of probabilities of lime treatment effects on soil and leaf nutrients in the Hutton and Oakleaf soil forms..... 48
Table 4.3	The effect of lime application on selected soil fertility properties in the Hutton and Oakleaf soil forms 49
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 49
Table 4.5	Critical thresholds for selected soil nutrient indices 50
Table 4.6	Critical threshold values for selected plant nutrient indices 51
Table 4.7	Non-linear regression analysis between relative yield and selected soil nutrients for pooled data in the Hutton and Oakleaf soil forms 53
Table 5.1	Correlation matrix for the relationship between maize grain yield, soil and leaf nutrients for the Hutton soil form..... 58
Table 5.2	Correlation matrix for relationship between maize grain yield, soil and leaf nutrients for the Oakleaf soil form..... 59
Table 5.3	Summary of the forward stepwise regression analysis for yield for the two experimental soils 60
Table 6.1	The range of selected soil physical and chemical topsoil (0-250 mm) properties ¹ for the experimental soils 68
Table 6.2	Mean values of selected soil physical and chemical topsoil (0-250 mm) properties ¹ for the dominant soil forms..... 70
Table 6.3	Correlation matrix for the relationship between soil buffer capacity and selected soil properties..... 72
Table 6.4	Summary of the forward stepwise regression analysis for buffer capacity at different pH ranges 73
Table 6.5	Correlation matrix obtained from principal component analyses between the variables and some scores 75
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 75
Table 7.1	Selected soil physical and chemical topsoil (0-250 mm) properties ¹ for the two dominant land uses in the Mlondozi district 86
Table 7.2	Summary of the forward stepwise regression analysis for soil BC and lime requirement (LR)..... 90
Table 7.3	Correlation matrix between lime requirement (LR), acidification rates (Δ pH unit year ⁻¹) and selected soil properties 100
Table 7.4	Non-linear regression analysis between various soil properties and acidification rate. 113

TABLE OF FIGURES

Figure 2.1	The relationships between relative grain yields and (a) soil pH (H ₂ O), (b) extractable Al, (c) extractable acidity and (d) acid saturation in all treatments of both experimental soils.	25
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 soils, respectively (***) P < 0.001, ** P < 0.01 and * P < 0.05).....	35
Figure 3.2	Relationship between measured and predicted acidification rates for the (a) Hutton and (b) Oakleaf soil form (***) P < 0.001, ** P < 0.01).	37
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.	38
Figure 3.4	Relationship between initial pH (H ₂ O) 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).	39
Figure 3.5	The relationships between extractable (Ca + Mg), and time in the (a) Hutton and (b) Oakleaf experimental soils.....	42
Figure 4.1	The relationship between relative yield and soil (a) K, (b) Ca, (c) Mg, and (d) Cu.	52
Figure 5.1	Nutrient vector analysis. Interpretation of directional changes in relative biomass and nutrient status of plants contrasting in growth (Timmer & Teng, 1999).	57
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.	62
Figure 6.1	Combined titration curves for the dominant soil types.	69
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.....	76
Figure 6.3	PCA evaluating the interrelationships between dominant soil forms, soil BC and other selected soil properties.....	78
Figure 7.1	Relationship between measured soil BC determined by potentiometric titrations and predicted soil BC according to Equation 7.6.	92
Figure 7.2	Critical soil pH values by means of broken-stick analysis between (a) pH (H ₂ O) and extractable (Al + H), and (b) pH (KCl) and extractable (Al + H), (c) pH (H ₂ O) and extractable Al and (d) pH (KCl) and extractable Al.	93
Figure 7.3	Relationship between measured lime requirement (tonnes CaCO ₃ ha ⁻¹) and predicted lime requirement according to Equation 7.7.....	101
Figure 7.4	The relationship between acidification rate (Δ pH year ⁻¹) and (a) soil pH (H ₂ O), (b) pH (KCl), (c) extractable Al, (d) extractable acidity, (e) ECEC (cmol _c kg ⁻¹ soil) and (f) clay content.....	112

TABLE OF MAPS

Map 1.1	Map of study area location in the Mpumalanga province.....	8
Map 1.2	Soil map of the Mlondozi district.....	11
Map 7.1	Location of study area and spatial distribution of sample points.....	82
Map 7.2	Interpolated map (1:200 000) of organic C values of the topsoil (0-250 mm) in the Mlondozi district.....	87
Map 7.3	Interpolated map (1:200 000) of clay values of the topsoil (0-250 mm) in the Mlondozi district.....	88
Map 7.4	Interpolated map (1:200 000) of CEC values of the topsoil (0-250 mm) in the Mlondozi district.....	88
Map 7.5	Interpolated map (1:200 000) of soil BC values of the topsoil (0-250 mm) in the Mlondozi district.....	91
Map 7.6	Interpolated maps (1:200 000) of current pH (H ₂ O) for the topsoil (0-250 mm) in the Mlondozi district.....	95
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.....	96
Map 7.8	Interpolated maps (1:200 000) of annual rainfall in the Mlondozi district.....	97
Map 7.9	Interpolated maps (1:200 000) of lime requirement (tonnes CaCO ₃ ha ⁻¹) from current pH (H ₂ O) to pH (H ₂ O) 6.0 in the Mlondozi district.....	98
Map 7.10	Interpolated map (1:200 000) of pH (H ₂ O) change per year for the topsoil (0-250 mm) in the Mlondozi district.....	103
Map 7.11	Interpolated map (1:200 000) of years until critical pH (H ₂ O) is reached for the topsoil (0-250 mm) in the Mlondozi district.....	104
Map 7.12	Interpolated map (1:200 000) of risk classes for the topsoil (0-250 mm) in the Mlondozi district.....	105
Map 7.13	Interpolated map (1:200 000) of simulating pH (H ₂ O) values for current pH for the topsoil (0-250 mm) in the Mlondozi district.....	107
Map 7.14	Interpolated map (1:200 000) of simulating pH (H ₂ O) values for 2 years for the topsoil (0-250 mm) in the Mlondozi district.....	108
Map 7.15	Interpolated map (1:200 000) of simulating pH (H ₂ O) values for 4 years and (d) 6 years for the topsoil (0-250 mm) in the Mlondozi district.....	109
Map 7.16	Interpolated maps (1:200 000) of simulating pH (H ₂ O) values for 6 years for the topsoil (0-250 mm) in the Mlondozi district.....	110

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 (H₂O), 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(H₂O) value of 5.33, and 0.140 pH unit year⁻¹ for an initial pH(H₂O) 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(H₂O) 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 CaCO₃ ha⁻¹ annually, while 0, 0.8 and 0.8 tonne CaCO₃ 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 (H₂O) 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 (H₂O) 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.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the following persons and institutions:

Professor Andries S Claassens and Dr Danie J Beukes, for their mentoring and guidance, and for their assistance in the preparation of this manuscript.

In addition, special thanks to Mr Leon de Beer and other extension staff of the Mpumalanga Department of Agriculture and Land Affairs.

Appreciation is expressed to Mr Filemon Mathunjwa and Mr Claas Zwane for donating the experimental sites and for logistical support.

My thanks to Mrs Marie Smith for statistical analyses.

The Agricultural Research Council and the National Department of Agriculture for funding.

Mr Simon Tshabalala, Charles Maseko, Catherine Nkosi and Eric Mashabane, extension officers in Mlondozi, for their assistance and advice.

Mr Marius van Rensburg from the Nooitgedacht Agriculture Development Centre for his assistance and advice.

Mr Michael Kidson, Mr Martiens Mmamadisha, Mr William Mashabane, Ms Rinda van der Merwe, Mr Roelof le Roux, Mrs Petro Ströhmenger, Mr Bates Booyens, Mr Louw Potgieter and Mr Willem Kirsten, from the ARC–Institute for Soil, Climate and Water, for their willingness and hard work in the execution of the project.

Mrs Esmè Lazenby and Mrs Anastasia Kgapane (ARC-ISCW) for research support with the demonstration trials at Mlondozi.

Dr Thomas Fyfield (ARC-ISCW) for editing this report.

My husband, Stephanus, and children, Carli and Mieke, my family and friends for their support and motivation.

Abba Father for guidance, perseverance and wisdom, to you Father the highest praise.