

Assessing the potential soil acidification risk under dryland agriculture in the Mlondozi district in the Mpumalanga Province of South Africa

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The farming community in the Mlondozi district in the Mpumalanga Province of South Africa has been part of a government liming intervention with the objective to ameliorate the serious soil acidity problem in the district. The current study was undertaken in order to evaluate the impact of the liming intervention and the risk of re-acidification of the soil due to natural and agricultural activities. Acid production in the 0-250 mm depth varied from a measured 0.21 to 10.31 (mean 3.70 kmol H⁺ ha⁻¹ year⁻¹) in crop production sites. Approximately 190 kg lime ha⁻¹ yr⁻¹ is required to maintain current soil pH levels under crop production. 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. The upper and lower critical pH(H₂O) were found to be between ca. 5.73 and 5.68. Below the lower critical value a reduction in crop production can be expected and above the upper critical value, accelerated acidification takes place. Soils with an extractable Al and acidity of <0.180 and <0.253 cmol (+) kg⁻¹ soil, respectively, a clay content of 26%, and an ECEC value of 3.29 cmol (+) kg soil⁻¹, or high initial soil pH values, are more at risk to accelerated acidification than soils with lower extractable Al and acidity, higher clay contents and higher ECEC values.

Keywords: Acidification rates, acid production loads, buffer capacity, lime requirement

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Introduction

High soil acidity and Al saturation are two of the major factors responsible for yield reduction 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 factors that contribute to soil acidification include the initial soil pH, soil buffering capacity, 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. Identifying areas that are at high risk of soil acidification is achieved through determining the number of years until a critical pH is reached, given the value of each of the contributing risk factors at a geographical location within the study area (Hill, 2003). 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 for various land uses in the Mlondozi district. Soil acidity indices, buffer capacity and soil acidification rates were determined for soils under crop production and natural rangeland used for cattle grazing over a period of

6 years. 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.

Material and methods

Study area

The Mlondozi district is situated between 26° 05' S - 26°30' S, and 30°44' E - 31°00' E and occupies a total area of 54 000 ha (Figure 1). This district is extremely hilly with altitudes varying from 1 700 m.a.s.l. in the north, dropping to 1 300 m.a.s.l. centrally and rising to 1 580 m.a.s.l. in the south. The long-term mean annual rainfall for the study area ranges between 893 to 992 mm from north to south. Monthly average daily temperature ranges from 10.2°C for the coldest month to 18.9°C for the hottest month. Historically the area was primarily used for seasonal grazing because of the climatic unsuitability for crop farming. 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, most of the district is at high risk of soil acidification.

Soil sampling and analysis

Representative soil samples were collected from two land uses, namely natural rangeland (natural grazing; 23 samples, ca. 50 000 ha) and dryland crop production (77 samples, ca. 4 000 ha). Figure 1 indicates the spatial distribution of sample points. The sampled soils represented the most dominant soil forms (Soil Classification Working Group, 1991), namely Magwa and Clovelly, with Inanda and Hutton soil forms sub-

dominant. Topsoil samples (0-250 mm) 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. Exchangeable cations, cation exchange capacity, soil organic carbon, extractable acidity and aluminium (Al), pH (H₂O) and (KCl), and free oxides of iron (Fe), Al and manganese (Mn) were determined according to the procedures of The Non-Affiliated Soil Analysis Work Committee (1990). Effective cation exchange capacity (ECEC) was determined as the sum of exchangeable cations (Al³⁺ + Ca²⁺ + Mg²⁺ + K⁺ + Na⁺) (Sumner and Noble, 2003). The double buffer SMP method of McLean *et al.* (1978) was used to determine the lime requirement of the soils.

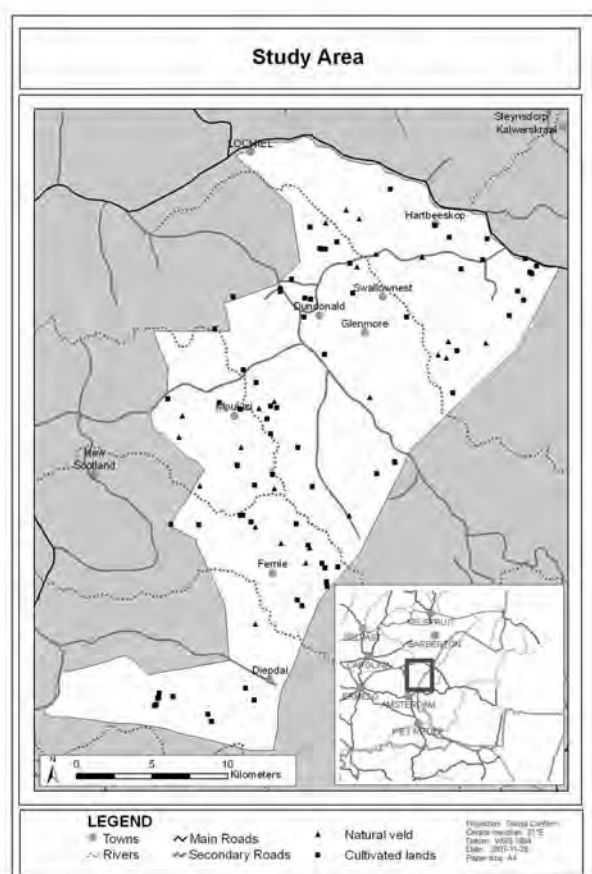


Figure 1 Location of study area and spatial distribution of sample points.

Soil buffer capacity (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 1, adapted from Bache (1988), was used to calculate soil BC.

$$\text{Soil BC } [(\text{cmol } (\text{H}^+) \text{ kg}^{-1} \text{ soil pH unit}^{-1})] = \Delta(\text{OH}^-) / \Delta \text{pH} \quad [1]$$

where ΔpH is the change in pH (pH unit) due to the addition of OH⁻ (cmol (+) kg soil⁻¹) as NaOH.

The soil BC calculated in Equation 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 2 as suggested by Singh *et al.* (2003):

$$\text{Soil BC } [(\text{kmol } \text{H}^+ (\text{ha}_{250 \text{ mm}})^{-1} (\text{pH unit})^{-1})] = (\text{BC} \times V \times \text{BD}) / 100\,000 \quad [2]$$

where V is volume of soil layer (m³ 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⁺).

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

The acid production load (kmol H⁺ (ha_{250mm})⁻¹ (year)⁻¹) was calculated with Equation 3 as described by Helyar and Porter (1989):

$$\text{APL} = (\Delta \text{pH} / \Delta t) \times \text{soil BC} \quad [3]$$

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

Estimates of soil acidification rate were calculated as follows:

The decrease in soil pH in one year (pH year⁻¹) was calculated with Equation 4 as reported by Singh *et al.* (2003), using the APL and soil BC:

$$\Delta \text{pH units year}^{-1} = \text{APL} / \text{soil BC} \quad [4]$$

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 5:

$$\text{Time (years)} = [(\text{pH}_{(\text{current})} - \text{pH}_{(\text{critical})}) \times (\text{soil BC})] / \text{APL} \quad [5]$$

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 CaCO₃ neutralizes 2 moles of H⁺ in the soil (Ridley *et al.*, 1990; Dolling *et al.*, 1994).

Spatial interpolation of soil properties and acidification risk

ArcGIS 9 (ESRI, 2006) was used to interpolate map surfaces for selected soil properties such as pH (H₂O), soil buffer capacity and lime requirement from 100 field sample points using the Inverse Distance Weighting interpolation method. 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. 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 5. Three risk classes were identified: class 1 (high-risk areas with pH values lower than critical pH

values; class 2 (moderate-risk areas expected to acidify to the critical pH in less than 5 years); and class 3 (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).

Statistical analysis

Data was analyzed using Genstat (2003). Pearson's correlations were calculated between all variates measured. Forward Selection Stepwise Regression was used to identify those soil parameters most responsible for describing the variation found in soil BC measurements and lime requirement. Critical values of properties were determined by the broken-stick analysis procedure (Genstat, 2003) where two straight line segments were statistically fitted through datasets that exhibited two distinct populations with linear relationships per

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

Results and discussion

General and spatial soil characteristics

Table 1 indicates selected soil chemical and physical properties of the main land uses, namely crop production and natural rangeland. 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. Soils were medium to heavy textured (sandy loam to clay soil texture classes), with medium (1.13%) to high (9.14%) organic C content (mean C values of 2.44 and 2.10% for crop and rangeland soils, respectively; Table 1).

Table 1 Selected soil physical and chemical topsoil (0-250 mm) properties 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 (cmol (+) kg^{-1}) | 3.34-14.09 | 7.18 | 6.83 | 3.59-11.73 | 7.79 | 6.79 |
| ECEC (cmol (+) kg^{-1}) | 0.78-12.72 | 4.99 | 4.58 | 2.62-10.31 | 6.00 | 5.31 |
| Extractable acidity (cmol (+) kg^{-1}) | 0-2.61 | 0.60 | 0.42 | 0.05-1.50 | 0.68 | 0.56 |
| Extractable Al (cmol (+) 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 (cmol (+) 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 |

Soil buffer capacity (BC)

The soils in the study area were medium to well buffered (Steinke *et al*, 2004) with soil BC values ranging from 0.124 to 2.217 cmol (H^+) kg^{-1} pH unit $^{-1}$, and means of 0.68 (rangeland) to 0.75 (crop production) cmol (H^+) kg^{-1} pH unit $^{-1}$ (Table 1). Figure 2 (a) 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 cmol (H^+) kg^{-1} pH unit $^{-1}$.

Forward stepwise multiple linear regression analyses indicated that extractable Al, CBD-Fe accounted for 88.4% for the variation in soil BC (Table 2). The relationship is given by Equation 6.

$$\text{Soil BC} = 0.842 + 0.653(\text{Al}) + 0.109(\log\text{CBD-Fe}) \quad [6]$$

Where Al is extractable Al (cmol (+) kg^{-1}), \log_e CBD-Fe (%).

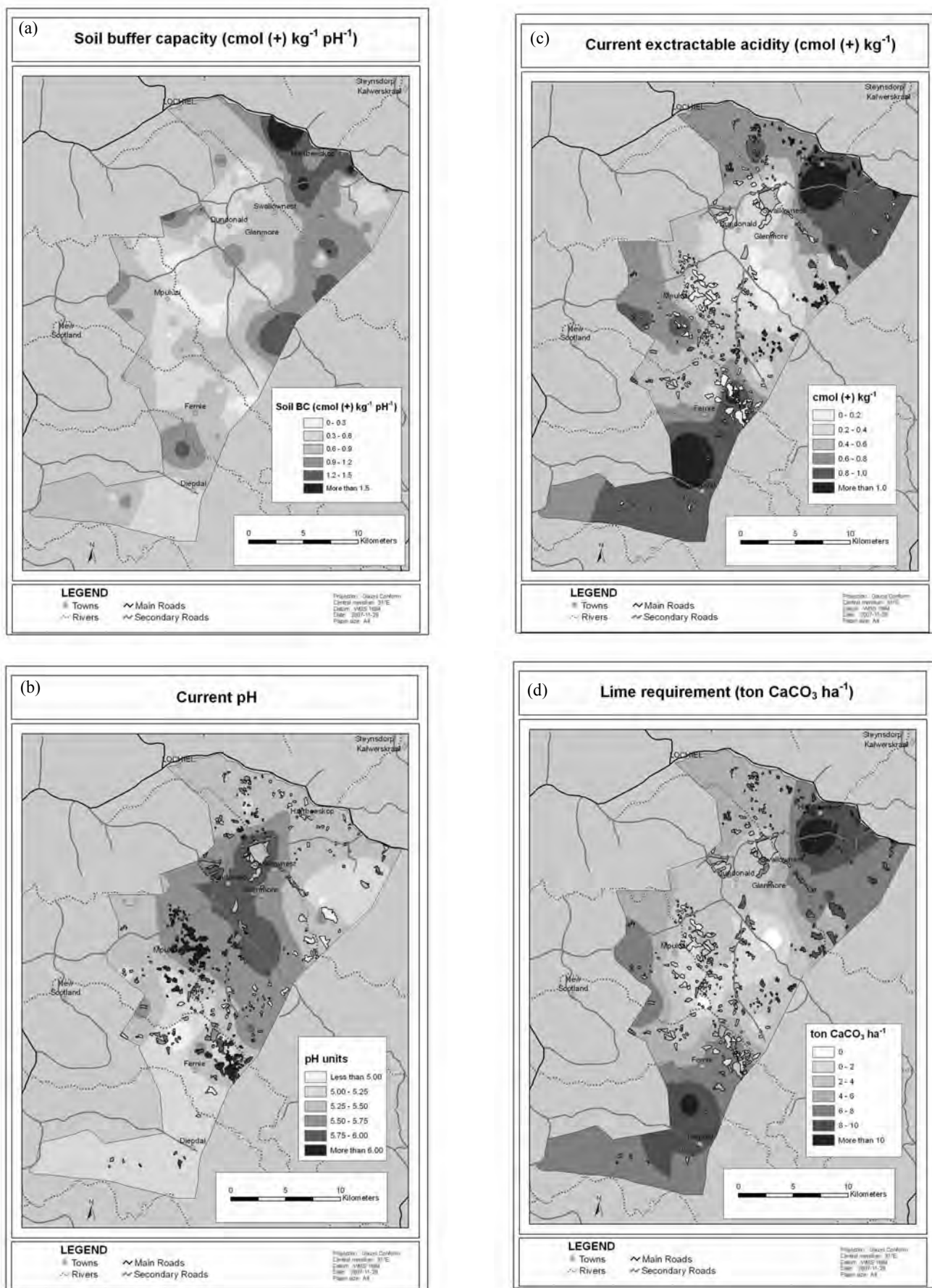


Figure 2 Interpolated maps (1:200 000) of (a) soil BC values, (b) current pH (H₂O), (c) extractable acidity (cmol (+) kg⁻¹) values and (d) lime requirement (ton CaCO₃ ha⁻¹) from current pH (H₂O) to pH (H₂O) 6.0 for the topsoil (0-250 mm) in the Mlondozhi district.

Table 2 Summary of the forward stepwise regression analysis for soil buffer capacity (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*** |
| 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 ₂ O) | 87.0 | 1.11* |

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

Figure 3 shows a strong relationship ($R^2=0.92$) between soil BC, determined by potentiometric titrations, and predicted soil BC values determined from Equation 6. The prediction of soil BC values was best at a measured soil BC value of 0.37 $\text{cmol}(\text{H}^+) \text{kg}^{-1} \text{pH unit}^{-1}$. A slight over estimation of soil BC was detected below this value and an under estimation of soil BC above this value.

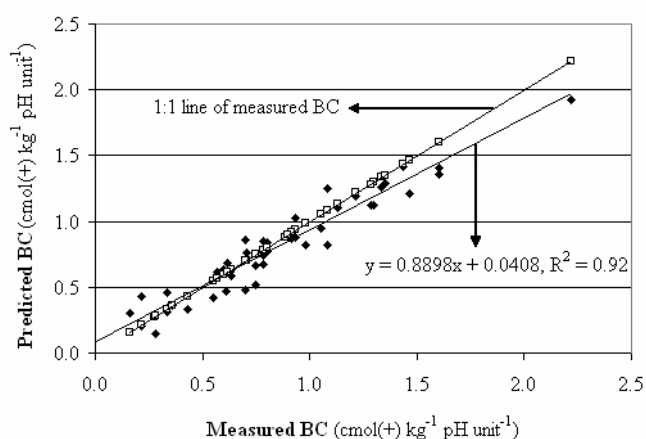


Figure 3 Relationship between measured soil BC determined by potentiometric titrations and predicted soil BC according to Equation 6.

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 4 indicates that intercepts for the two lines occurred at $\text{pH}(\text{H}_2\text{O}) = 5.68$ for extractable (Al + H) and extractable Al.

At $\text{pH}(\text{H}_2\text{O})$ of 5.68, extractable (Al + H) values of 0.25 $\text{cmol}(\text{H}^+) \text{kg}^{-1}$ and extractable Al of 0.17 $\text{cmol}(\text{H}^+) \text{kg}^{-1}$ was recorded. Above this pH, extractable Al levels were low and regression slopes approached zero. This observation is consistent with previous observations that extractable Al was essentially eliminated above $\text{pH}(\text{H}_2\text{O})$ 5.5 (Coleman & Thomas, 1967; Juo, 1977; Farina *et al.*, 1980).

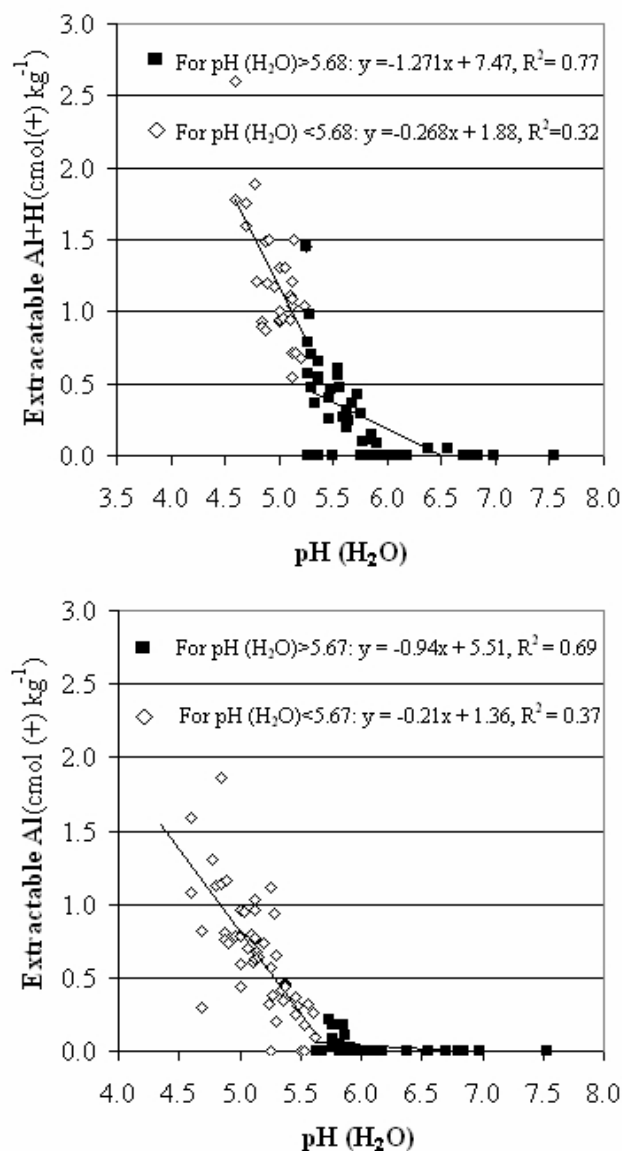


Figure 4 Critical soil pH values by means of broken-stick analysis between (a) $\text{pH}(\text{H}_2\text{O})$ and extractable (Al + H), and (b) $\text{pH}(\text{H}_2\text{O})$ and extractable Al.

Table 3 Correlation matrix between lime requirement (LR), acidification rates (pH unit year⁻¹) and selected soil properties

| | LR | Acid rate | pH (H ₂ O) | 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 ₂ O) | -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

Actual soil acidity indices and lime requirement (LR)

Actual pH (H₂O) and extractable acidity (cmol (+) kg⁻¹) interpolated maps (1:200 000 scale) are shown in Figure 2 (b, c). 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, probably due to the disturbance of the natural soil chemical processes due to cultivation.

The double buffer SMP method (McLean *et al.*, 1978) was used to determine lime requirements to attain a pH (H₂O) 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 lime requirements.

Table 3 reveals that properties such as extractable acidity (Al +H) or Al, organic C, pH (H₂O) and acid saturation are individually highly correlated (P<0.001) with lime requirement.

Forward selection stepwise regression analysis (Table 2) was used to assess the contribution of various soil parameters to lime requirement as given by Equation 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 (H₂O) increased the explained variation to 87.0%.

$$LR = -1.75 + 3.07(Al) - 17.45(\text{clay}/(\text{OC} \times \text{clay}) - 66.7(\text{OC}/\text{clay}) + 3.45(\text{pH}(\text{H}_2\text{O})) \quad [7]$$

where LR is lime requirement (ton pure CaCO₃ ha⁻¹), Al is extractable Al (cmol (+) 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 5.

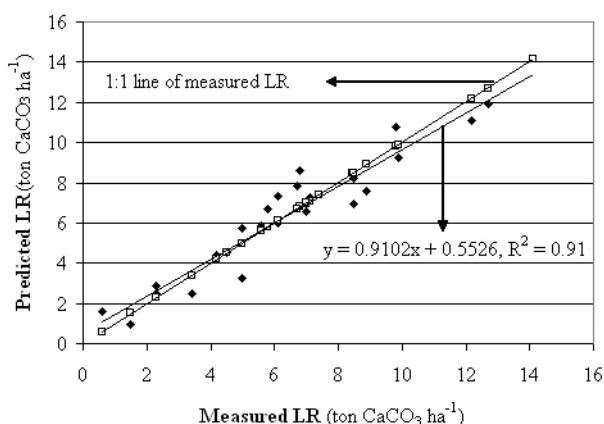


Figure 5 Relationship between measured lime requirement (ton CaCO₃ ha⁻¹) and predicted lime requirement according to Equation 7.

The prediction of LR values attained maximum accuracy at a measured lime requirement of 6.15 ton CaCO₃ ha⁻¹. A slight overestimation of lime requirement was detected below this value and an underestimation of lime requirement above this value. Figure 2 (d) shows a map of the interpolated lime

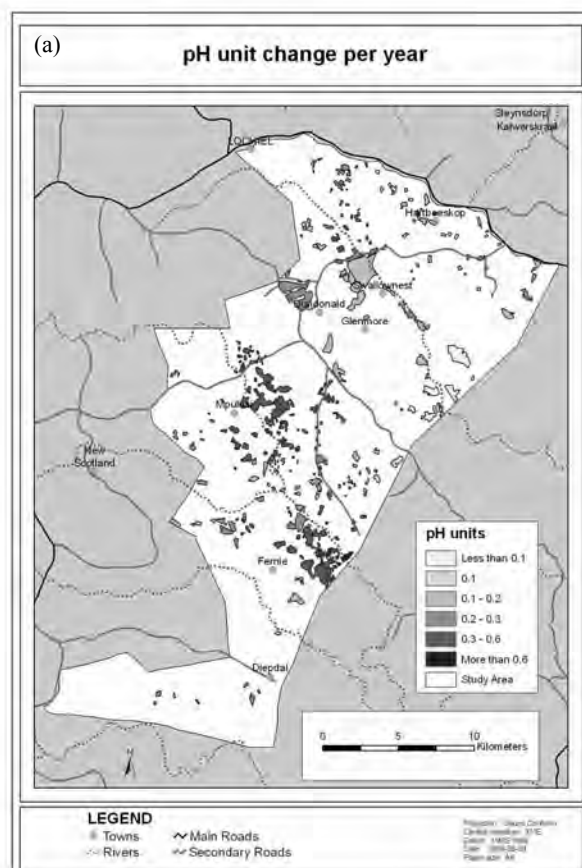
requirement values for the study area. Soils with high lime requirement values corresponded with areas of high soil BC values (compare Figures 2 (a) and 2 (d)).

Acid production load (APL)

In order to determine APL (using Equation 2), medium-term changes in soil pH (H₂O) values for 35 dryland crop production sites (mainly maize) were used in the study area. APL 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 CaCO₃ ha⁻¹ year⁻¹, with a mean of 190 kg CaCO₃ 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.

Acidification risk assessment

In order to spatially simulate the decline in soil pH (H₂O) of the topsoil (0-250 mm) over time, APLs were combined with geostatistics. Interpolated acidification risk maps were created at a 1:200 000 scale using pH (H₂O) per annum, years until the critical pH(H₂O) of 5.68 is reached and a spatial risk classification of the district (Figure 6 (a-c)).



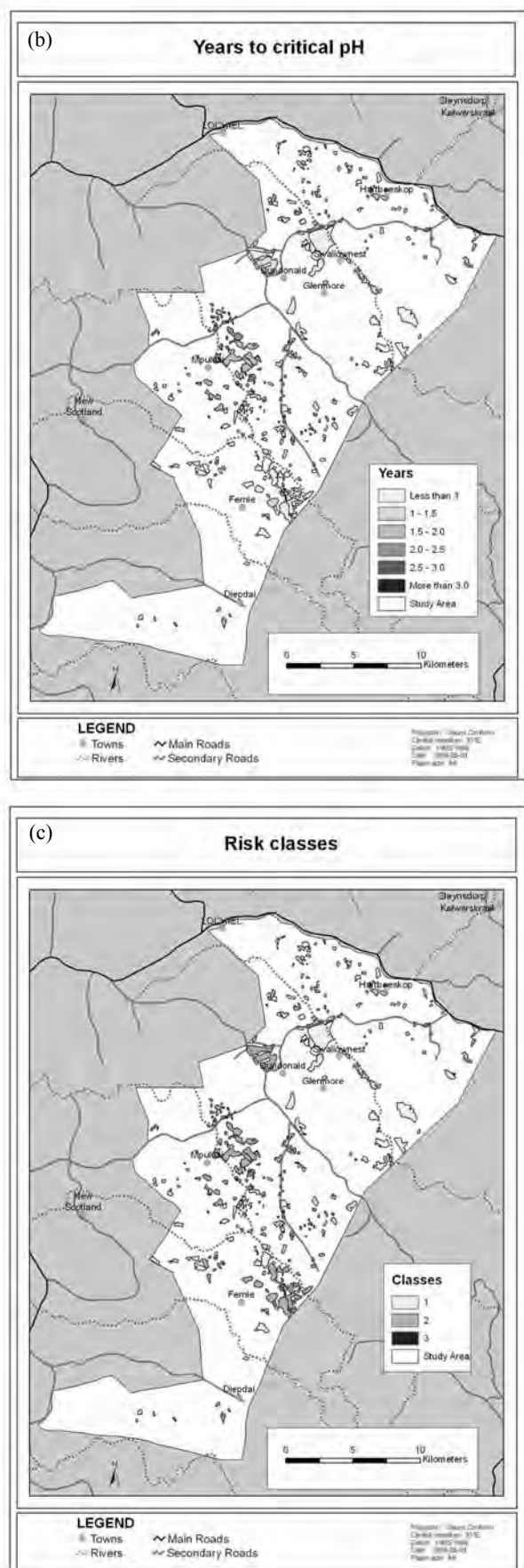


Figure 6 Interpolated maps (1:200 000) of (a) pH (H₂O) change per year, (b) years until critical pH (H₂O) is reached and (c) risk classes for the topsoil (0-250 mm) in the Mlondozi district.

Figure 6 (a) 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 expected number of years until a given critical pH is reached (Figure 6 (b)) enables acidification risk predictions (Figure 6 (c)) to be made by identifying the bracket within which the number of years falls (Hill, 2003). Figure 6 (b) shows that within two years the pH(H₂O) 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(H₂O) was already lower than the critical pH (Figure 6 (c)).

Relationship between acidification rate and selected soil properties

Table 3 shows that several soil properties were highly significantly ($P < 0.001$) correlated with acidification rate.

Soil pH(H₂O) and pH(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 3 and Figure 7 show that acidification rate (pH unit year⁻¹) was high if the initial soil pH(H₂O 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 due to increased decomposition rates of organic matter, resulting in a release of reduced forms of N and S. Furthermore, at high pH values, extractable Al is essentially eliminated and does not contribute to buffering. And lastly, increase pH leads to optimal conditions for nitrification (Gasser, 1973; Hoyt & Henning, 1982; Matzner & Meiwes, 1994) that resulted in high production of H⁺. Table 4 and Figure 7 show critical soil parameters where acceleration in acidification could be expected.

Table 4 Non-linear regression analysis between various soil properties and acidification rate.

| Variables | R ² (%) | F | Critical value |
|----------------------------|--------------------|-----------|--------------------------------------|
| Soil pH (H ₂ O) | 57.72 | 102.39*** | 5.73 |
| Extractable Al | 47.48 | 69.60*** | 0.180 cmol (+) kg soil ⁻¹ |
| Extractable acidity | 47.92 | 70.84*** | 0.253 cmol (+) kg soil ⁻¹ |
| ECEC | 43.63 | 38.06*** | 3.29 cmol (+) kg soil ⁻¹ |
| Clay | 29.20 | 28.45*** | 26.10% |

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

Figure 7 (a) shows that above a critical pH (H₂O) value of 5.73, acidification rates are accelerated. Critical threshold values for extractable Al and acidity were recorded as <0.180 and 0.253 cmol (+) kg soil⁻¹ (Table 4). Below these critical values acceleration in acidification could be expected (Figure 7 (c, d)). Table 4 and Figure 7 (e) shows that the acidification rate as affected by ECEC, is the highest when this value drops

below 3.29 cmol (+) kg soil⁻¹. Table 4 and Figure 7 (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 clay content higher than 26.1%.

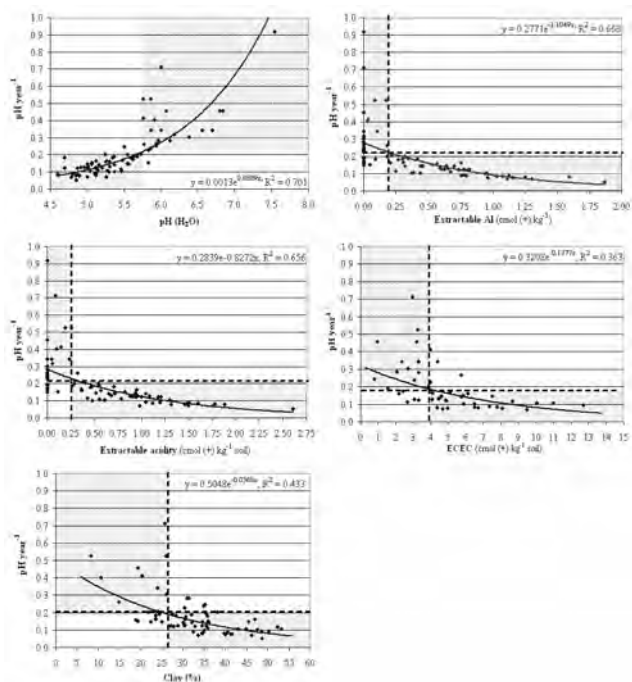


Figure 7 The relationship between acidification rate (pH year⁻¹) and (a) soil pH (H₂O), (b) pH (KCl), (c) extractable Al, (d) extractable acidity, (e) ECEC (cmol (+) kg⁻¹ soil) and (f) clay content.

Conclusions and recommendations

The farming community in the Mlondozi district has to make a living on soil where pH(H₂O) 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. 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 ton CaCO₃ ha⁻¹ year⁻¹ to maintain current soil acidification rates in the Mlondozi district. From a strategic perspective, it is recommended that acid production rates and the maintenance liming amounts be quantified in the study area to assist producers, extension officers, and policy makers in making decisions towards preventing acidification and the long-term impact of a production system.

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