

## 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

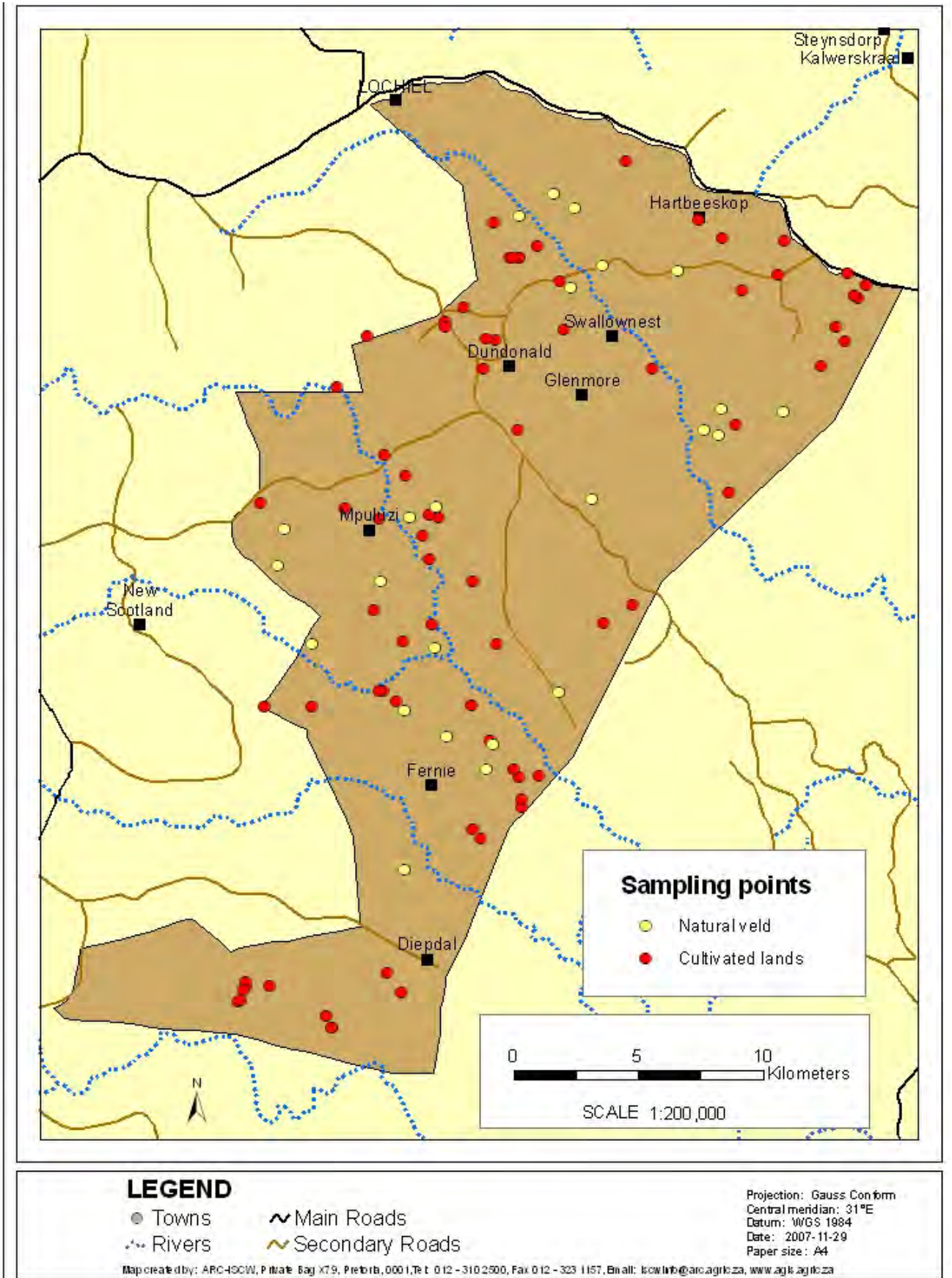
the MDACE. Soil acidity indices, soil BC and soil acidification rates were determined for soils under crop production and natural rangeland used for cattle grazing. Furthermore, risk maps and management tools were developed for land users and extension personnel to manage soil acidification in a resource-poor farming area at Mlondozi.

## **7.2 MATERIAL AND METHODS**

### **7.2.1 Study area**

The Mlondozi district is situated between 26° 05' S - 26°30' S, and 30°44' E - 31°00' 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 10.2°C for the coldest month to 18.9°C 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,  $\approx 50\,000$  ha) and dryland crop production (66 samples,  $\approx 4\,000$  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<sub>2</sub>O) 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<sup>-1</sup>. 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).

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

where  $\Delta\text{pH}$  is the change in pH (pH unit) due to the addition of OH<sup>-</sup> (cmol<sub>c</sub> kg soil<sup>-1</sup>) as NaOH.

The soil BC calculated in Equation 7.1 was converted to (kmol H<sup>+</sup> (ha<sub>250 mm</sub>)<sup>-1</sup> (pH unit)<sup>-1</sup>) using an average soil bulk density of 1300 kg m<sup>-3</sup> using Equation 7.2 as suggested by Singh *et al.* (2003):

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

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

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

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

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

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

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

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

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:

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

where  $\text{pH}_{(\text{current})}$  is the current pH,  $\text{pH}_{(\text{critical})}$  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  $\text{CaCO}_3$  neutralizes 2 moles of  $\text{H}^+$  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 ( $\text{H}_2\text{O}$ ), 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 ( $\text{H}_2\text{O}$ ) values, using an average APL of  $3.70 \text{ kmol (H}^+) \text{ ha}^{-1} \text{ year}^{-1}$  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<sub>2</sub>O) 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<sub>4</sub>OAC (pH 7) extraction, and ECEC is the sum of extractable cations (Al<sup>3+</sup> + H<sup>+</sup> + Ca<sup>2+</sup> + Mg<sup>2+</sup> + K<sup>+</sup> + Na<sup>+</sup>) (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.

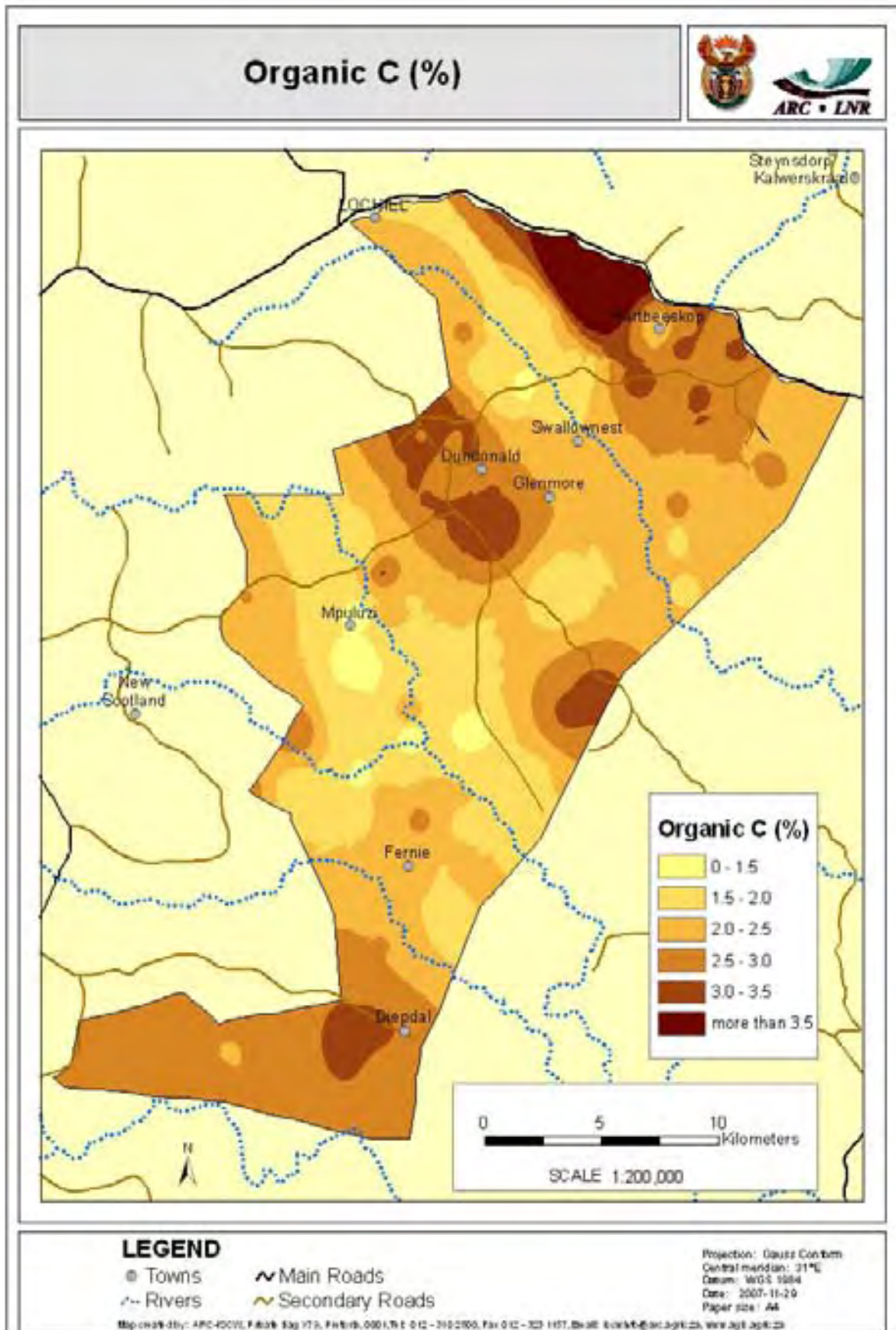
**Table 7.1** Selected soil physical and chemical topsoil (0-250 mm) properties<sup>1</sup> for the two dominant land uses in the Mlondozi district

Soil property	Land use					
	Crop production			Natural rangeland		
	Range	Mean	Median	Range	Mean	Median
pH (H <sub>2</sub> O)	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 <sub>c</sub> kg <sup>-1</sup> )	3.34-14.09	7.18	6.83	3.59-11.73	7.79	6.79
ECEC (cmol <sub>c</sub> kg <sup>-1</sup> )	0.78-12.72	4.99	4.58	2.62-10.31	6.00	5.31
Extractable acidity (cmol <sub>c</sub> kg <sup>-1</sup> )	0-2.61	0.60	0.42	0.05-1.50	0.68	0.56
Extractable Al (cmol <sub>c</sub> kg <sup>-1</sup> )	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 <sub>c</sub> kg <sup>-1</sup> pH unit <sup>-1</sup> )	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

<sup>1</sup> According to the The Non-Affiliated Soil Analysis Work Committee (1990)

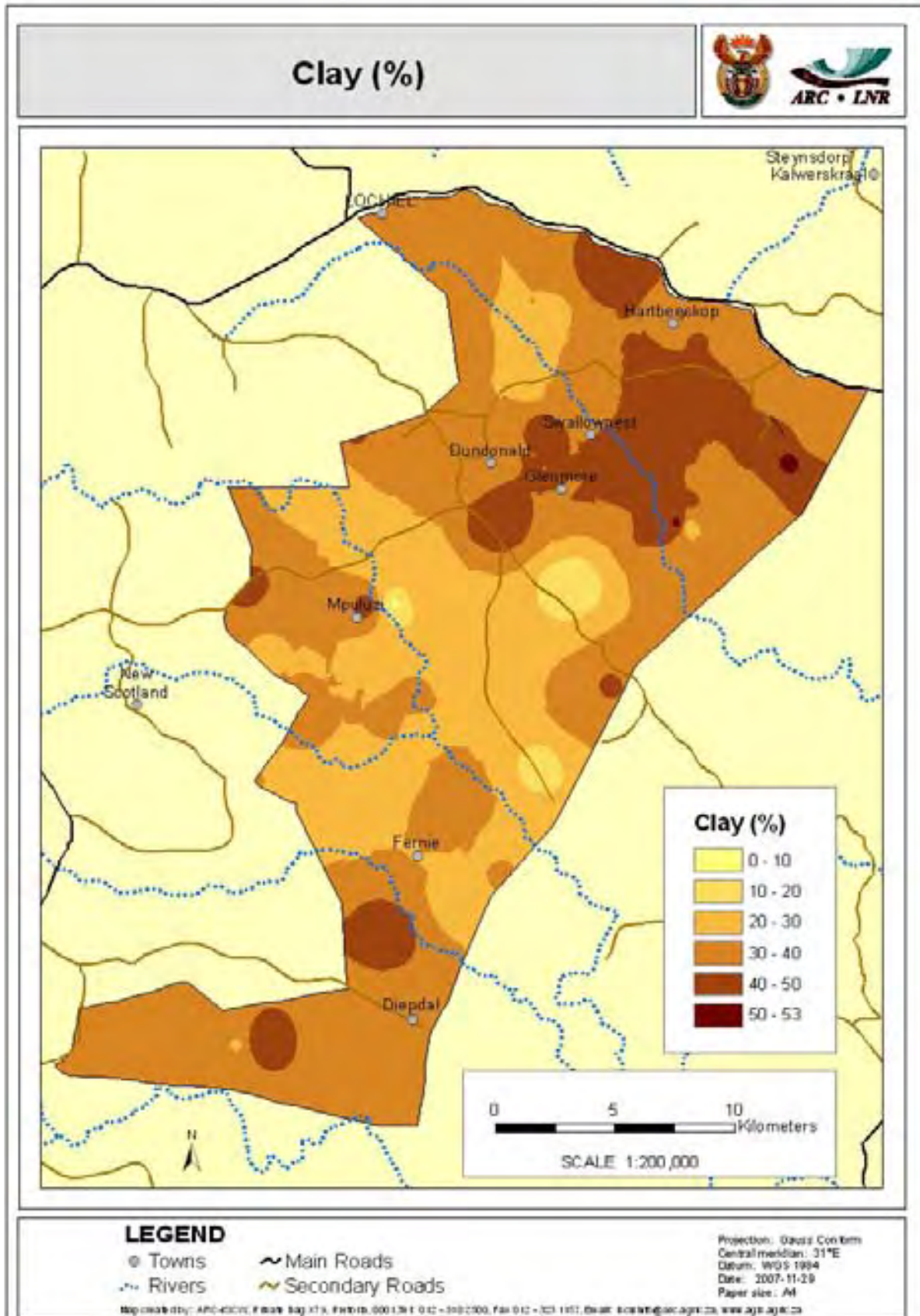
### 7.3.2 Soil buffer capacity

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 cmol<sub>c</sub> kg<sup>-1</sup> pH unit<sup>-1</sup>, and means of 0.68 (rangeland) to 0.75 (crop production) cmol<sub>c</sub> kg<sup>-1</sup> pH unit<sup>-1</sup> (Table 7.1).



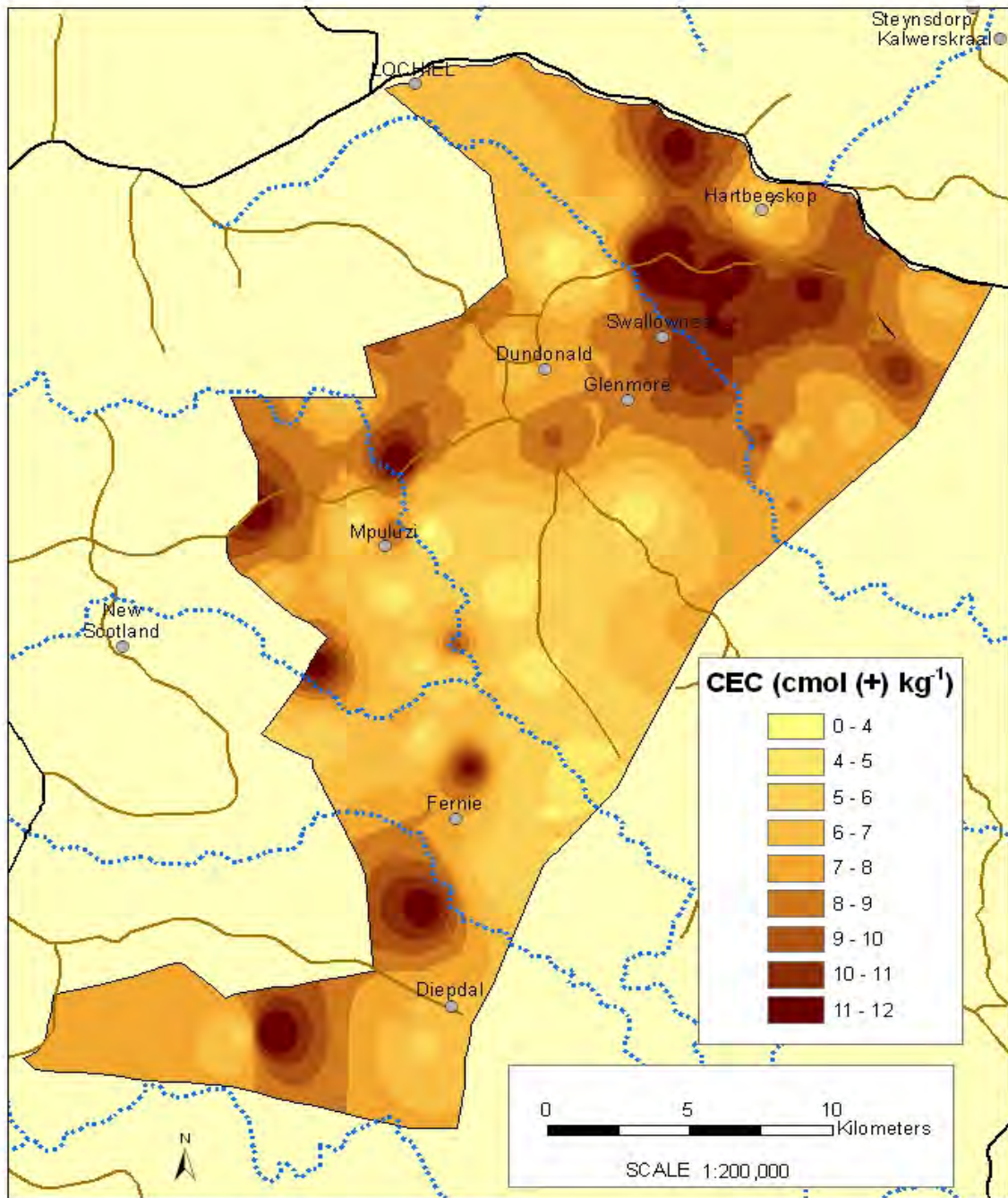
**Map 7.2** Interpolated map (1:200 000) of organic C values of the topsoil (0-250 mm) in the Mlondozi district.





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

**Cation exchange capacity (cmol (+) kg<sup>-1</sup>)**



**LEGEND**

- Towns
- ~ Main Roads
- ~ Rivers
- ~ Secondary Roads

Projection: Gauss Conform  
 Central meridian: 31°E  
 Datum: WGS 1984  
 Date: 2007-11-29  
 Paper size: A4

Map created by: ARC-ISCW, Private Bag X79, Pretoria, 0001, Tel: 012-310 2500, Fax 012-323 1157, Email: iswinfo@arc.agric.za, www.agric.za

**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  $0.9 \text{ cmol}_c \text{ kg}^{-1} \text{ pH unit}^{-1}$ . 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  $\text{BC}_{(4.5-8.5)}$ . Forward stepwise multiple linear regression analyses indicated that extractable Al, CBD-Fe, clay content and pH ( $\text{H}_2\text{O}$ ) accounted for 91.4% for the variation in soil BC (Table 7.2). The relationship is given by Equation 7.6.

$$\text{BC} = 0.842 + 0.653(\text{Al}) + 0.109(\log\text{CBD-Fe}) + 0.0085(\text{clay}) - 0.13(\text{pH}(\text{H}_2\text{O})) \quad [7.6]$$

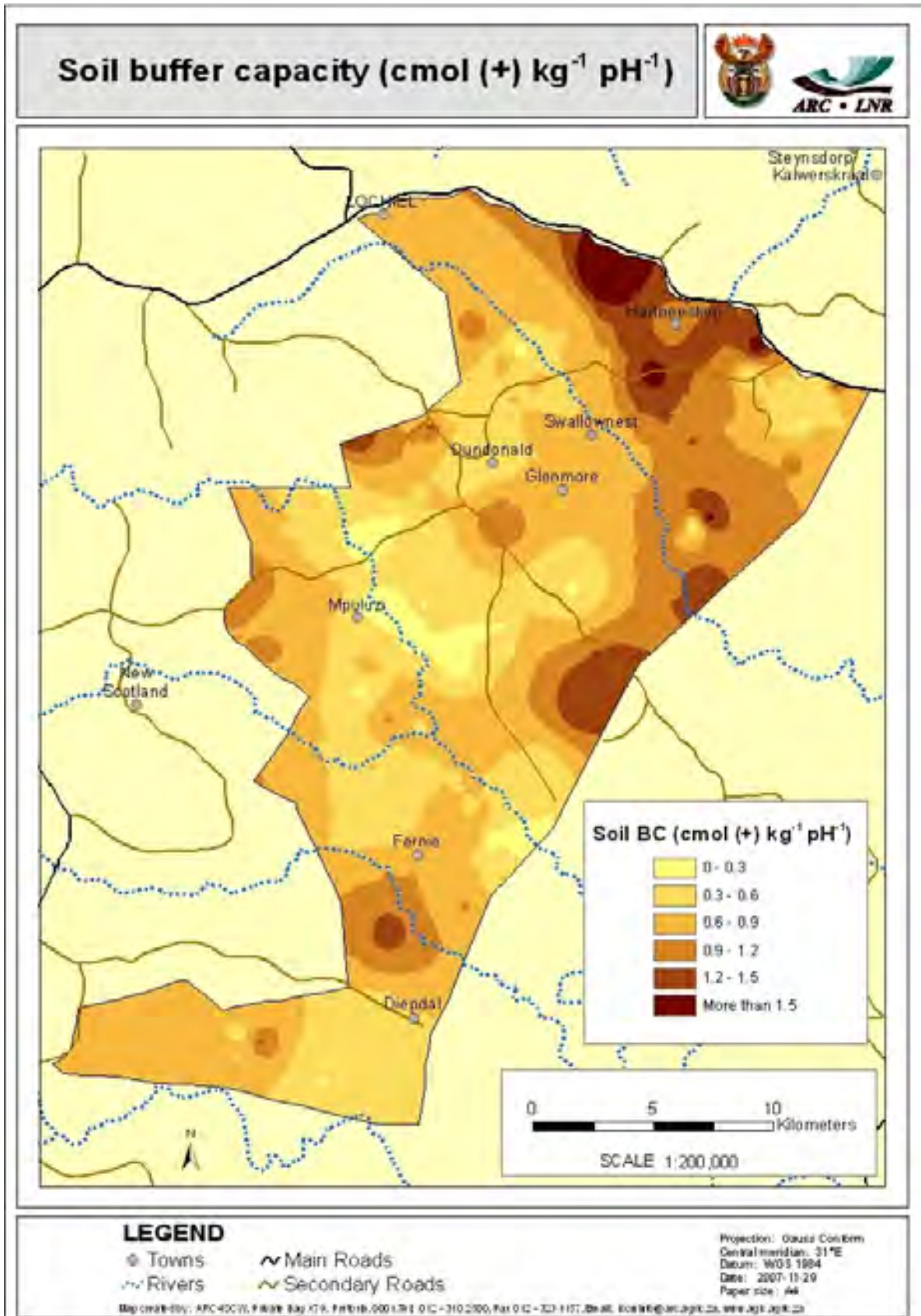
where soil BC is buffer capacity ( $\text{cmol}_c \text{ kg}^{-1} \text{ pH unit}^{-1}$ ), Al is extractable Al ( $\text{cmol}_c \text{ kg}^{-1}$ ),  $\log_e\text{CBD-Fe}$  (%), clay (%) and pH ( $\text{H}_2\text{O}$ ).

**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
<b>Soil BC</b>	Extractable Al	80.1	0.187***
	+ Fe-CBD	88.4	0.143***
	+ clay	89.4	0.136**
	+ pH ( $\text{H}_2\text{O}$ )	90.3	0.131*
<b>LR</b>	Extractable Al	57.6	2.00***
	+ (clay/(organic C x clay))	78.2	1.44***
	+ (organic C/clay)	84.6	1.21**
	+ pH ( $\text{H}_2\text{O}$ )	87.0	1.11*

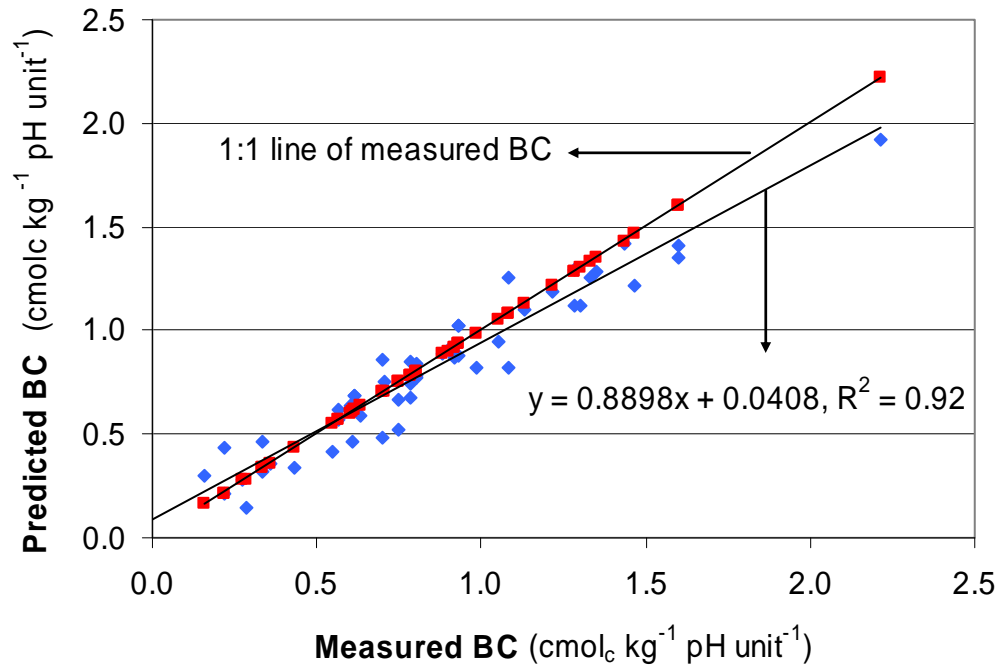
\*\*\*  $P < 0.001$ , \*\*  $P < 0.01$ , \*  $P < 0.05$





**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 potentiometric 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  $0.37 \text{ cmol}_c \text{ kg}^{-1} \text{ pH unit}^{-1}$ . A slight over estimation of soil BC was detected below this value and an under estimation of soil BC above this value.



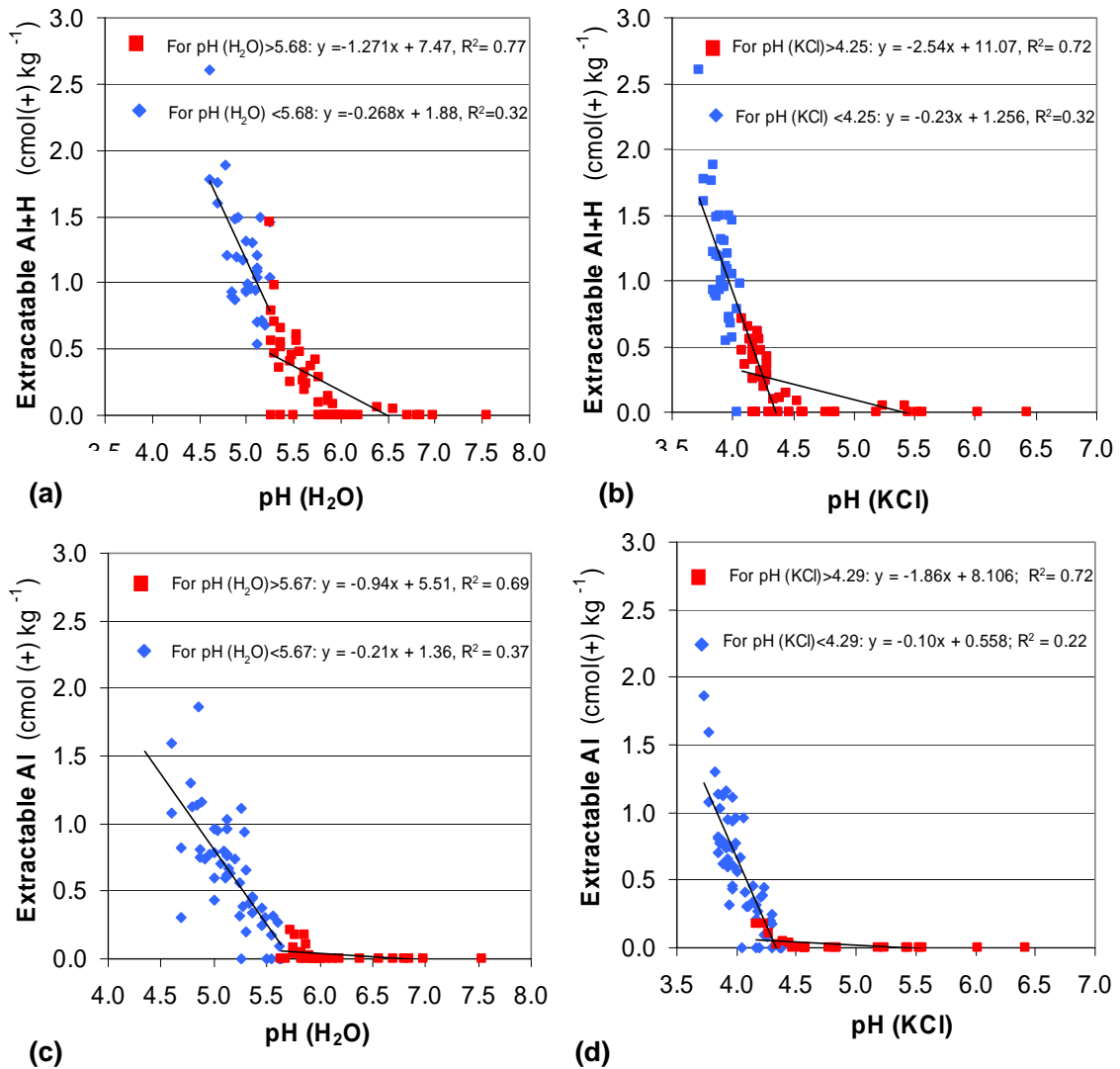
**Figure 7.1** Relationship between measured soil BC determined by potentiometric titrations and predicted soil BC according to Equation 7.6.

### 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<sub>2</sub>O) = 5.68 and pH (KCl) = 4.25 for extractable (Al + H), and pH (H<sub>2</sub>O) = 5.67 and pH (KCl) = 4.29 for extractable Al.

Extractable (Al + H) values of  $0.27$  and  $0.25 \text{ cmol}_c \text{ kg}^{-1}$  were recorded at pH (KCl) and pH (H<sub>2</sub>O) 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<sub>2</sub>O), the extractable Al was  $0.13$  and  $0.17 \text{ cmol}_c \text{ kg}^{-1}$ , respectively. At pH (KCl)= $4.29$  and pH (H<sub>2</sub>O)= $5.68$ , 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<sub>2</sub>O) and extractable (Al + H), and (b) pH (KCl) and extractable (Al + H), (c) pH (H<sub>2</sub>O) and extractable Al and (d) pH (KCl) and extractable Al.

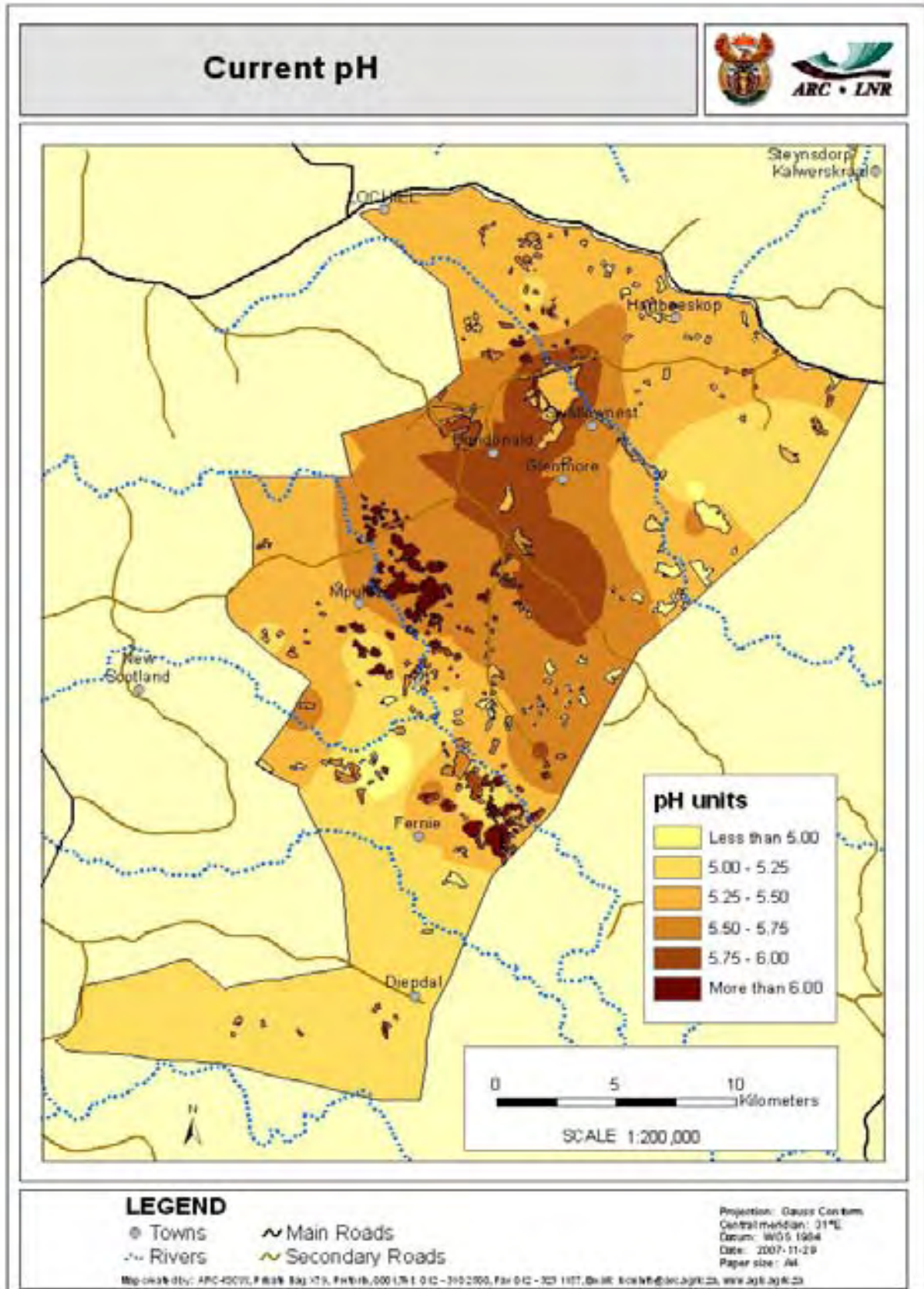
This observation is consistent with previous observations that extractable Al was essentially eliminated above pH (H<sub>2</sub>O) 5.5 (Coleman & Thomas, 1967; Sanchez, 1976; Juo, 1977; Farina *et al.*, 1980).

### 7.3.4 Actual soil acidity indices and lime requirement (LR)

Actual pH (H<sub>2</sub>O) and extractable acidity (cmol<sub>c</sub> kg<sup>-1</sup>) 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

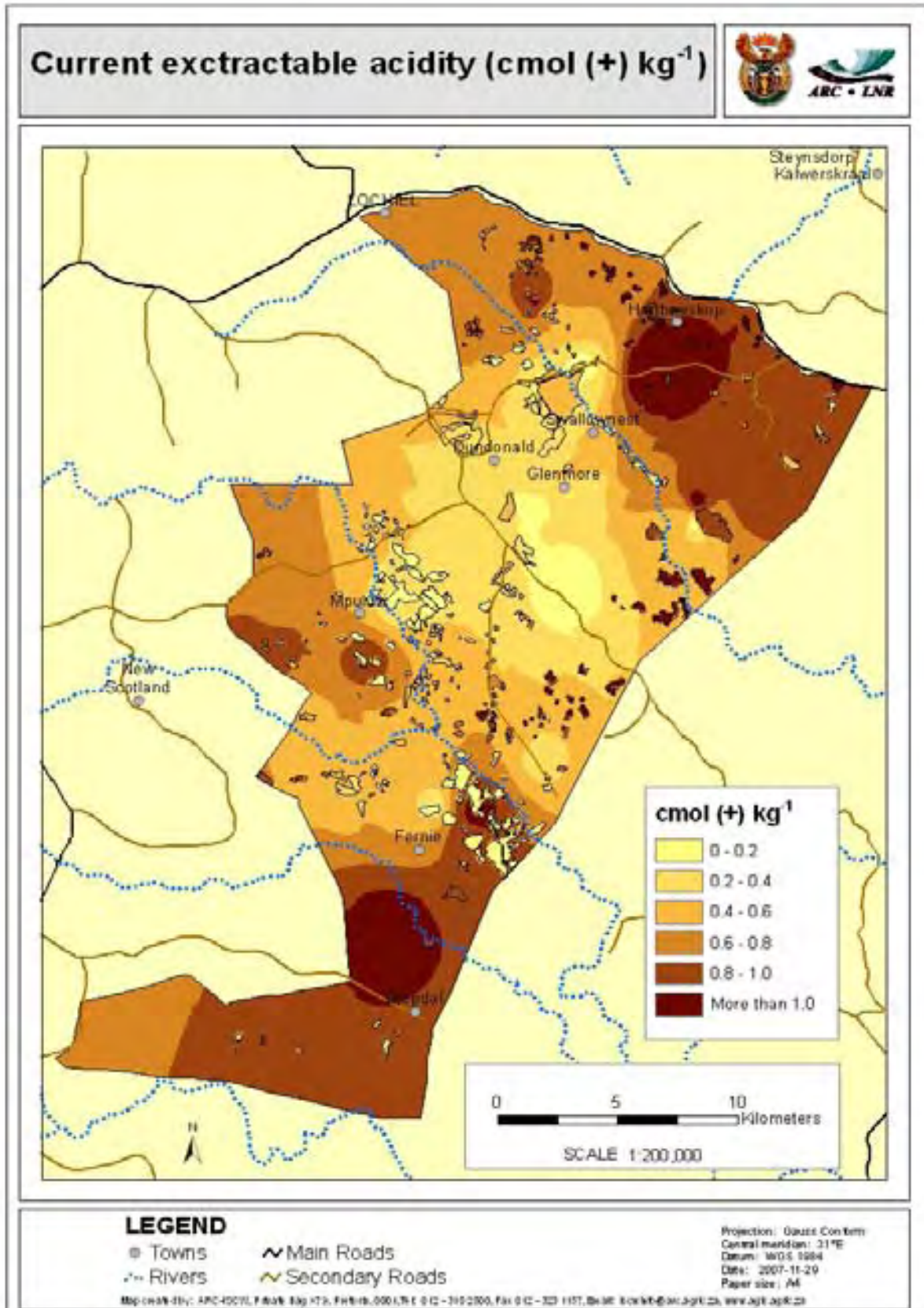
around Fernie and Diepdal. There was no clear trend in soil pH and extractable acidity values for cultivated fields with values that varied from lower, similar and higher than surrounding baseline values of natural veld.

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.

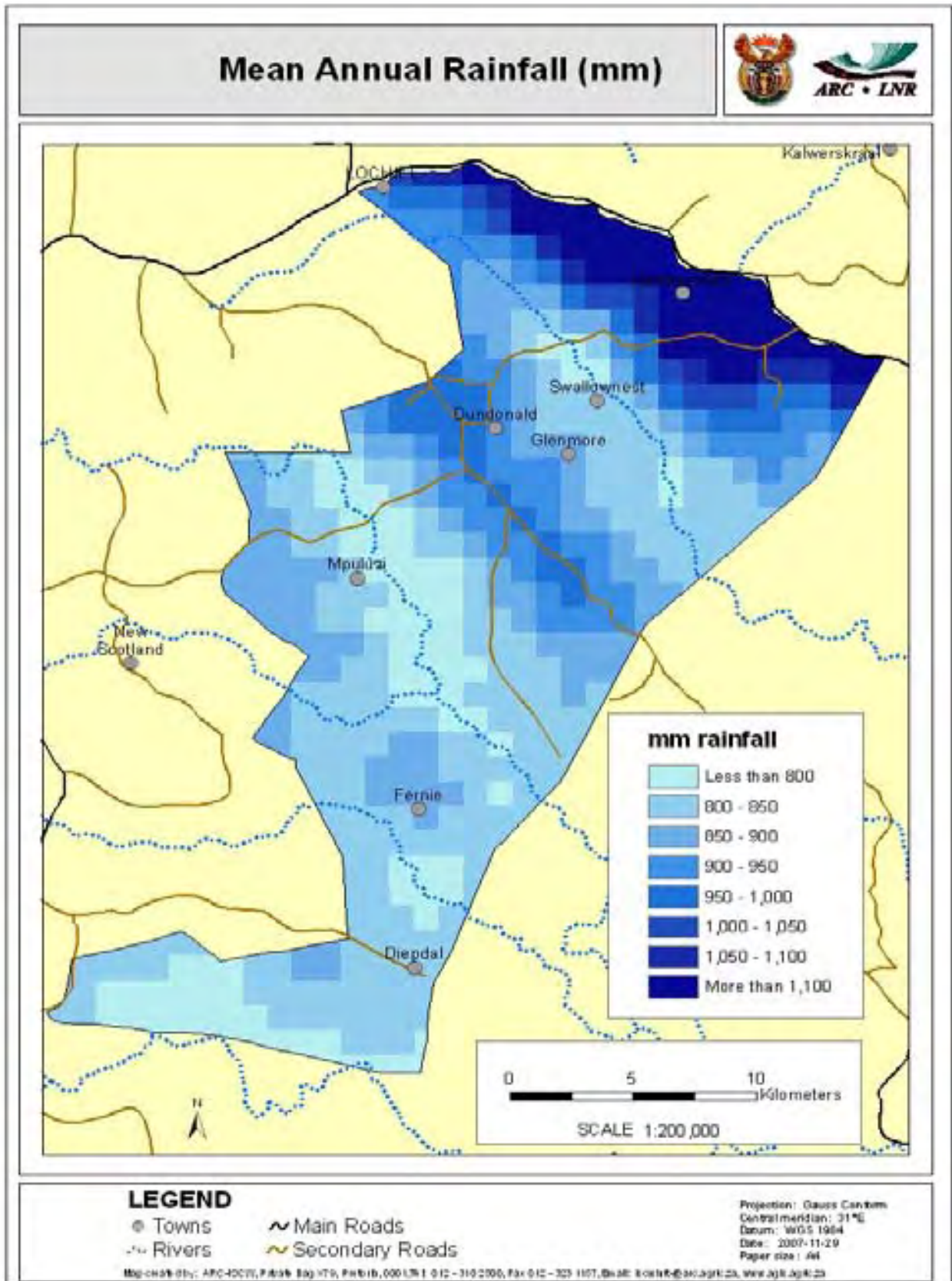


**Map 7.6** Interpolated maps (1:200 000) of current pH (H<sub>2</sub>O) for the topsoil (0-250 mm) in the Mlondozi district.



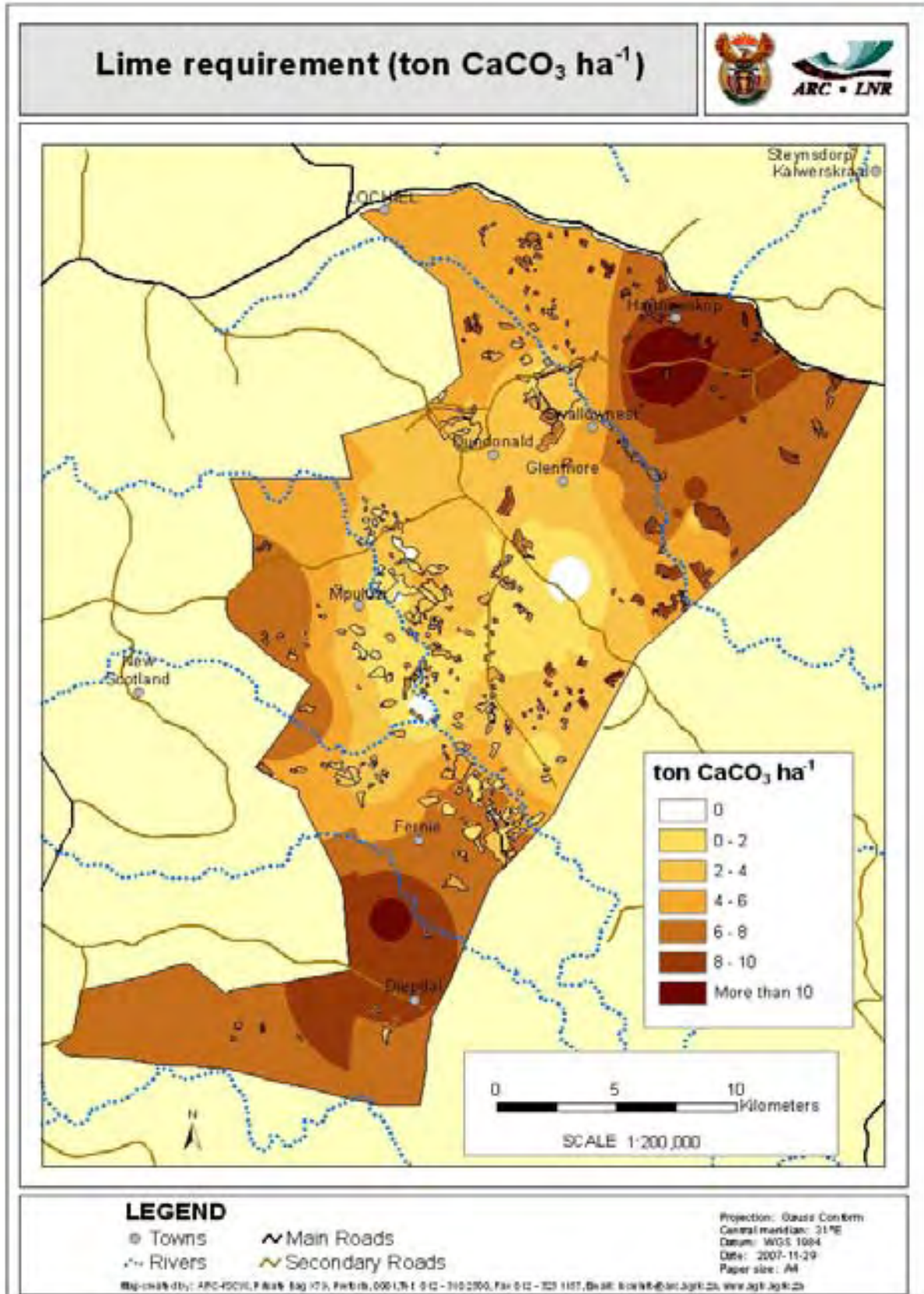


**Map 7.7** Interpolated maps (1:200 000) of current extractable acidity (cmol<sub>c</sub> kg<sup>-1</sup>) values for the topsoil (0-250 mm) in the Mlondozi district.



**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<sub>3</sub> ha<sup>-1</sup>) from current pH (H<sub>2</sub>O) to pH (H<sub>2</sub>O) 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<sub>2</sub>O) 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<sub>2</sub>O) 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<sub>2</sub>O) increased the explained variation to 87.0%.

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

where LR is lime requirement (tonnes pure CaCO<sub>3</sub> ha<sup>-1</sup>), Al is extractable Al (cmol<sub>c</sub> kg soil<sup>-1</sup>), 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<sub>3</sub> ha<sup>-1</sup>. A slight overestimation of lime requirement was detected below this value and an underestimation of lime requirement above this value.

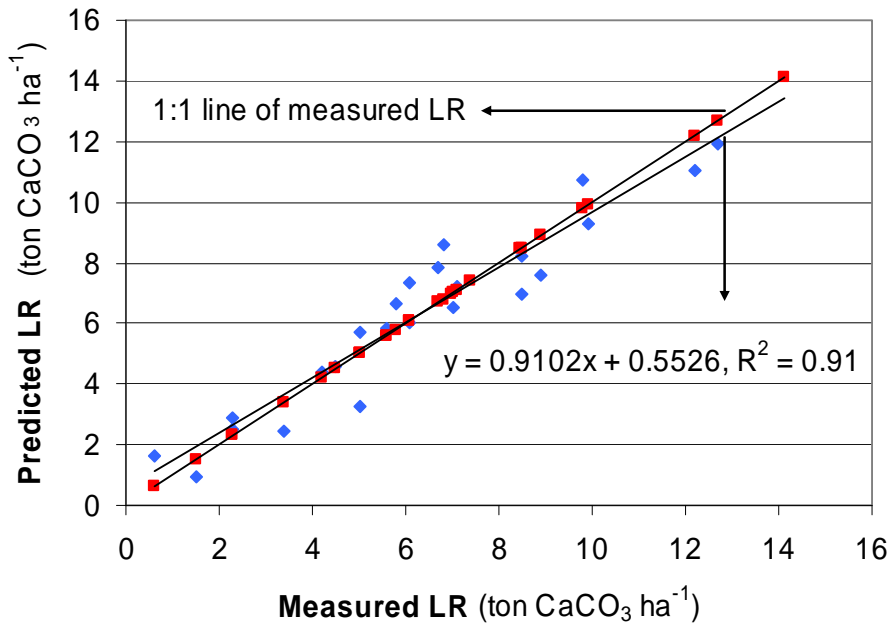
Map 7.9 shows a map of the interpolated lime requirement values for the study area. Soils with high lime requirement values corresponded with areas of high soil BC values (compare Maps 7.5 and 7.9). Areas around Hartbeeskop and Diepdal showed the highest lime requirement values of 8 tonnes CaCO<sub>3</sub> ha<sup>-1</sup> and higher to raise pH (H<sub>2</sub>O) values to 6.0 to a depth of 0-250 mm.



**Table 7.3** Correlation matrix between lime requirement (LR), acidification rates ( $\Delta$  pH unit year<sup>-1</sup>) and selected soil properties

	LR	Acid rate	pH (H <sub>2</sub> 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 <sub>2</sub> O)	<b>-0.627<sup>***</sup></b>	<b>0.724<sup>***</sup></b>														
pH(KCl)	-0.120	<b>0.628<sup>***</sup></b>	<b>0.881<sup>***</sup></b>													
Extr. Ac.	<b>0.686<sup>***</sup></b>	<b>-0.595<sup>***</sup></b>	<b>-0.847<sup>***</sup></b>	<b>-0.813<sup>***</sup></b>												
Al	<b>0.717<sup>***</sup></b>	<b>-0.607<sup>***</sup></b>	<b>-0.855<sup>***</sup></b>	<b>-0.806<sup>***</sup></b>	<b>0.978<sup>***</sup></b>											
Acid sat.	0.105	<b>-0.531<sup>***</sup></b>	<b>-0.862<sup>***</sup></b>	<b>-0.832<sup>***</sup></b>	<b>0.940<sup>***</sup></b>	<b>0.905<sup>***</sup></b>										
Ca	-0.037	0.087	<b>0.456<sup>***</sup></b>	<b>0.492<sup>***</sup></b>	<b>-0.523<sup>***</sup></b>	<b>-0.493<sup>***</sup></b>	<b>-0.599<sup>***</sup></b>									
Mg	0.005	0.093	<b>0.520<sup>***</sup></b>	<b>0.526<sup>***</sup></b>	<b>-0.503<sup>***</sup></b>	<b>-0.487<sup>***</sup></b>	<b>-0.597<sup>***</sup></b>	<b>0.939<sup>***</sup></b>								
Org. C	<b>0.682<sup>***</sup></b>	<b>-0.428<sup>***</sup></b>	-0.288 <sup>*</sup>	-0.224	<b>0.411<sup>***</sup></b>	<b>0.431<sup>***</sup></b>	0.198	-0.026	0.002							
Clay	<b>0.605<sup>***</sup></b>	<b>-0.562<sup>***</sup></b>	-0.297 <sup>*</sup>	-0.127	0.298 <sup>*</sup>	0.300 <sup>**</sup>	0.117	0.158	0.202	<b>0.716<sup>***</sup></b>						
CEC	0.297	<b>-0.408<sup>***</sup></b>	-0.104	-0.030	0.221	0.197	0.044	0.383 <sup>**</sup>	<b>0.480<sup>***</sup></b>	<b>0.550<sup>***</sup></b>	<b>0.744<sup>***</sup></b>					
ECEC	-0.178	<b>-0.495<sup>***</sup></b>	-0.339 <sup>**</sup>	-0.282 <sup>*</sup>	<b>0.492<sup>***</sup></b>	<b>0.432<sup>***</sup></b>	0.358 <sup>**</sup>	-0.075	0.036	<b>0.581<sup>***</sup></b>	<b>0.708<sup>***</sup></b>	<b>0.879<sup>***</sup></b>				
CBD-Al	0.385 <sup>*</sup>	<b>-0.466<sup>***</sup></b>	-0.361 <sup>**</sup>	-0.248 <sup>*</sup>	<b>0.393<sup>***</sup></b>	<b>0.404<sup>***</sup></b>	0.276 <sup>*</sup>	-0.057	-0.047	<b>0.722<sup>***</sup></b>	<b>0.678<sup>***</sup></b>	<b>0.458<sup>***</sup></b>	<b>0.511<sup>***</sup></b>			
CBD-Fe	0.285	<b>-0.417<sup>***</sup></b>	-0.105	0.062	0.056	0.072	-0.093	<b>0.452<sup>***</sup></b>	<b>0.463<sup>***</sup></b>	<b>0.551<sup>***</sup></b>	<b>0.799<sup>***</sup></b>	<b>0.801<sup>***</sup></b>	<b>0.635<sup>***</sup></b>	<b>0.637<sup>***</sup></b>		
CBD-Mn	-0.336	-0.317 <sup>**</sup>	-0.002	0.072	-0.001	0.017	-0.143	<b>0.466<sup>***</sup></b>	<b>0.523<sup>***</sup></b>	0.331 <sup>*</sup>	<b>0.564<sup>***</sup></b>	<b>0.810<sup>***</sup></b>	<b>0.635<sup>***</sup></b>	0.286 <sup>*</sup>	<b>0.750<sup>***</sup></b>	
Kt	0.397 <sup>*</sup>	0.016	-0.181	-0.101	0.016	0.039	0.067	-0.056	-0.083	-0.300 <sup>*</sup>	-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<sub>3</sub> ha<sup>-1</sup>) 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<sub>2</sub>O) 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<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup>, 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<sub>3</sub> ha<sup>-1</sup> year<sup>-1</sup>, with a mean of 190 kg CaCO<sub>3</sub> ha<sup>-1</sup> year<sup>-1</sup> in the crop production sites. The APLs recorded in the study (mean of 1.39 kmol (H<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup> 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<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup> 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<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup>) and kikuyu pastures (21.3 kmol (H<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup>).

### 7.3.6 Acidification risk assessment

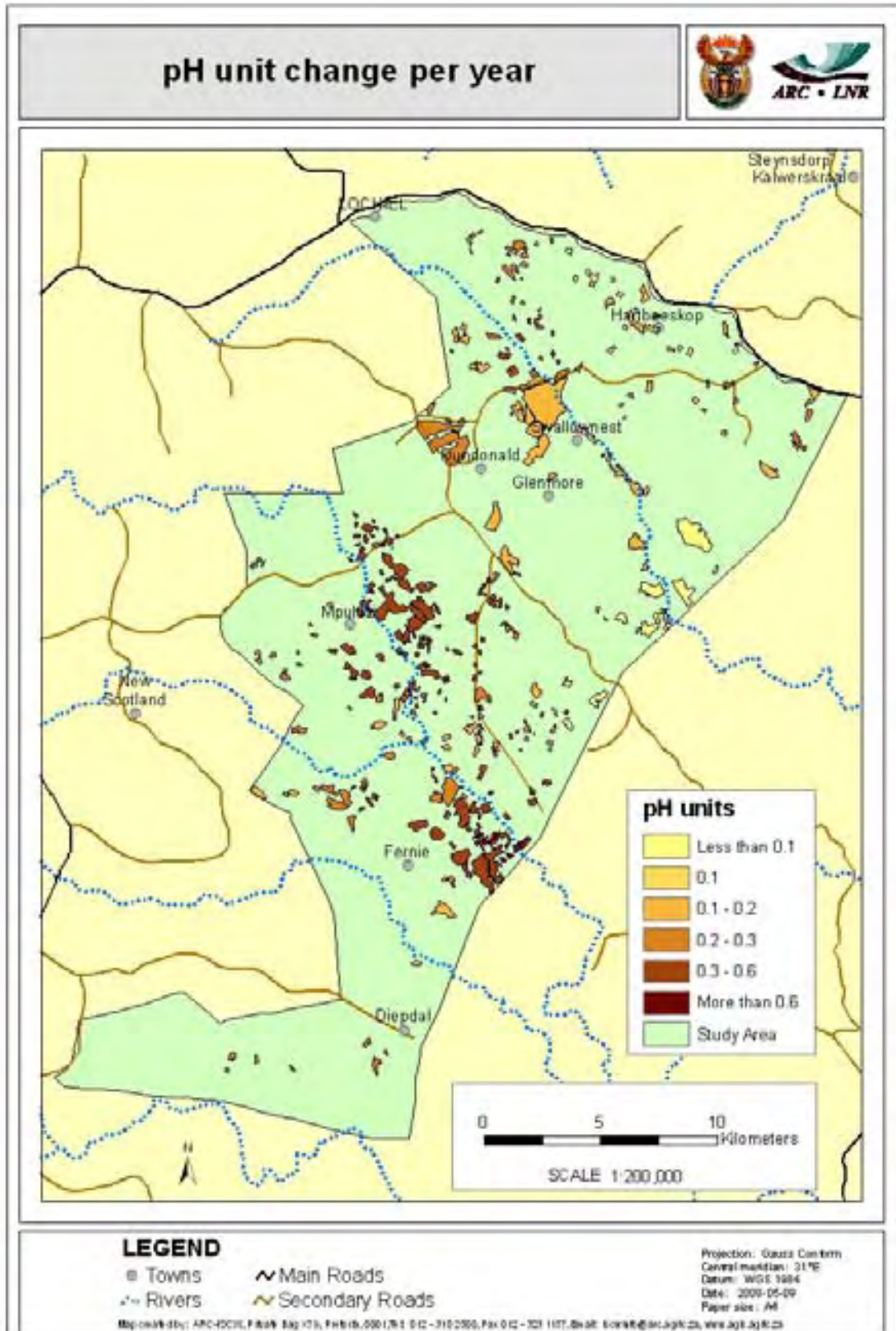
In order to spatially simulate the decline in soil pH (H<sub>2</sub>O) of the topsoil (0-250 mm) over time, acid

production loads were combined with geostatistics. Interpolated acidification risk maps were created at a 1:200 000 scale using pH (H<sub>2</sub>O) change per annum ( $\Delta$  pH unit year<sup>-1</sup>), years until the critical pH (H<sub>2</sub>O) of 5.68 is reached and a spatial risk classification of the district (Maps 7.10 to 7.12).

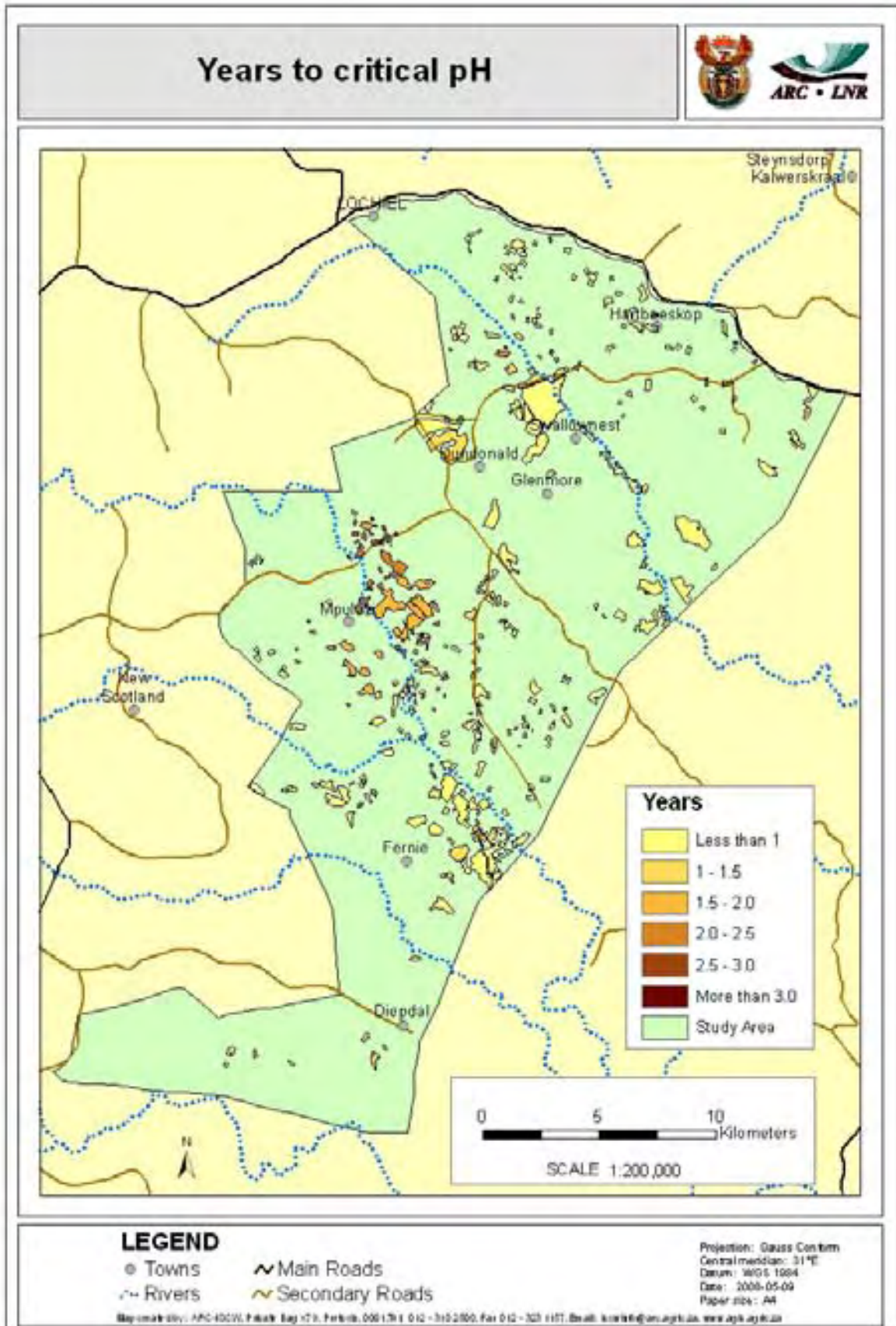
Map 7.10 indicates that the rate of pH decline for the top 250 mm soil depth was between 0.051 and 0.918 (mean 0.237) units year<sup>-1</sup>, with the fastest rates on the crop production sites in the Mpuluzi and Fernie areas characterized by lower soil BC values. The acid generated from crop production practices (3.70 kmol (H<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup>) 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<sub>4</sub><sup>+</sup> 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).



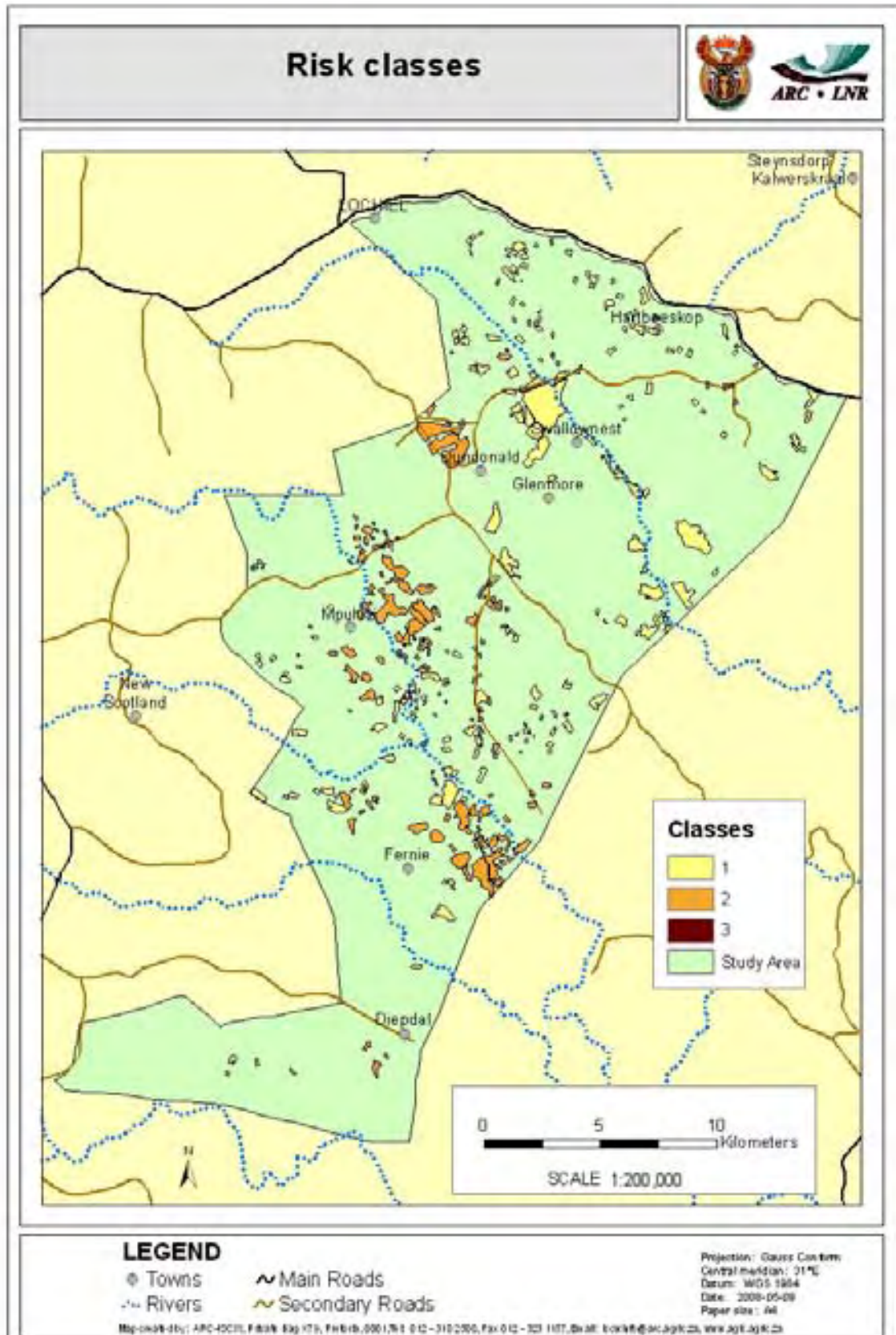


**Map 7.10** Interpolated map (1:200 000) of pH (H<sub>2</sub>O) change per year for the topsoil (0-250 mm) in the Mlondozi district.



**Map 7.11** Interpolated map (1:200 000) of years until critical pH (H<sub>2</sub>O) is reached for the topsoil (0-250 mm) in the Mlondozi district.





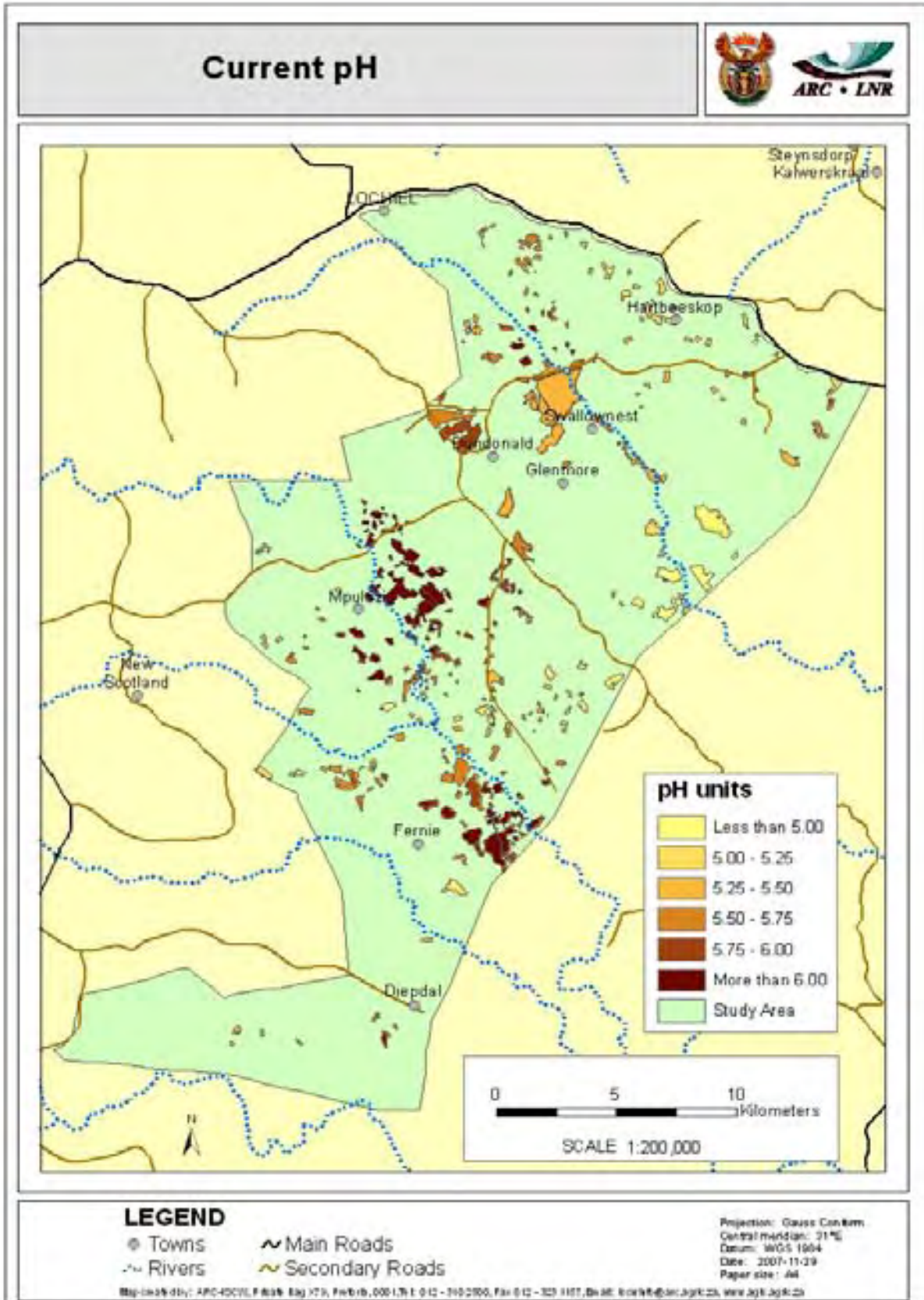
**Map 7.12** Interpolated map (1:200 000) of risk classes for the topsoil (0-250 mm) in the Mlondozi district.

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.

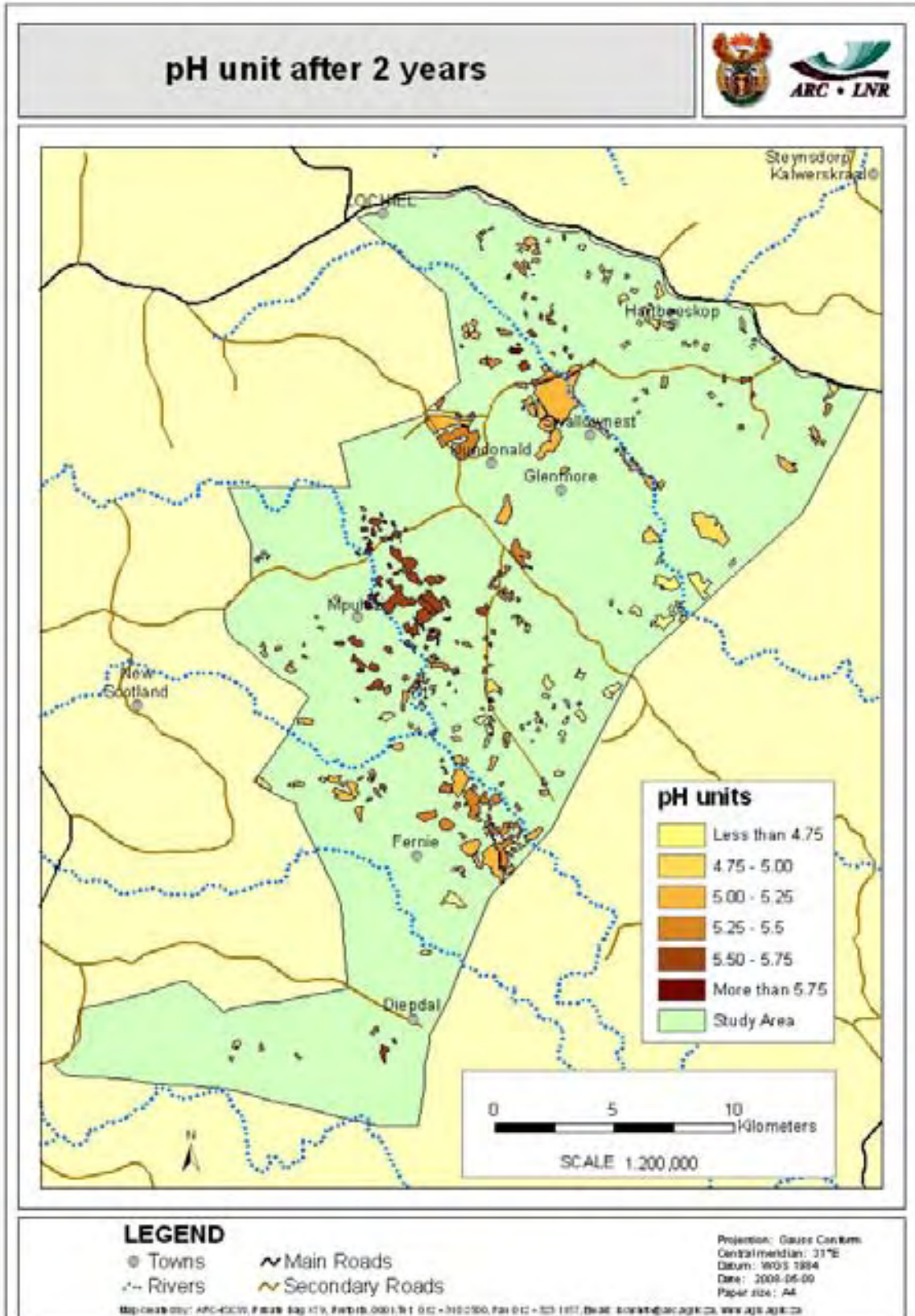
Maps 7.13 to 7.16 shows interpolated maps (1:200 000 scale) simulating pH ( $H_2O$ ) values for a sequence of current, 2, 4 and 6 years. Compared with the current situation, a dramatic reduction in pH ( $H_2O$ ) values could be expected within the relatively short period of 6 years. Generally the high 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  $3.70 \text{ kmol } (H^+) \text{ ha}^{-1} \text{ year}^{-1}$ .

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.





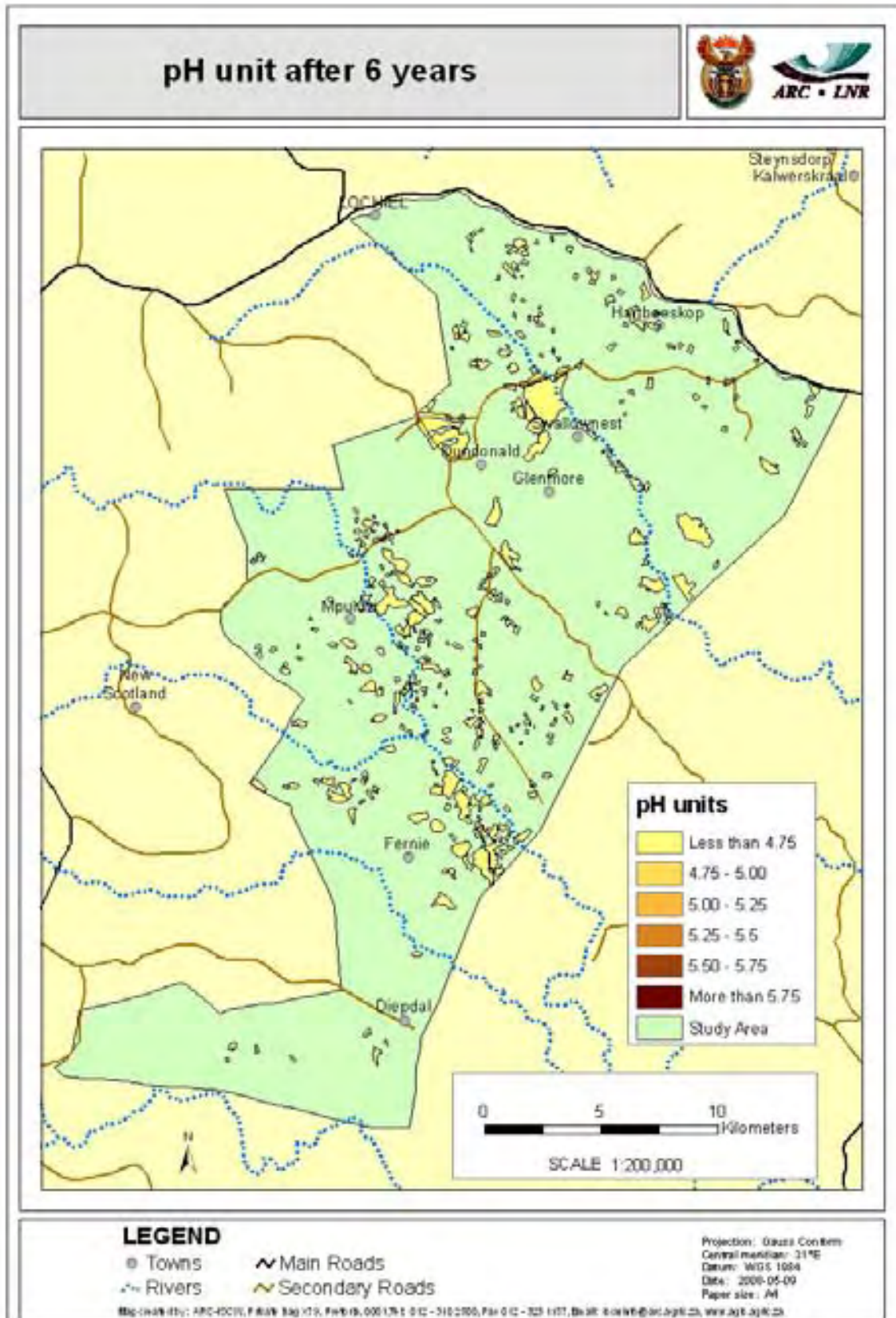
**Map 7.13** Interpolated map (1:200 000) of simulating pH (H<sub>2</sub>O) values for current pH for the topsoil (0-250 mm) in the Mlondozi district.



**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 7.16** Interpolated maps (1:200 000) of simulating pH (H<sub>2</sub>O) values for 6 years for the topsoil (0-250 mm) in the Mlondozi district.

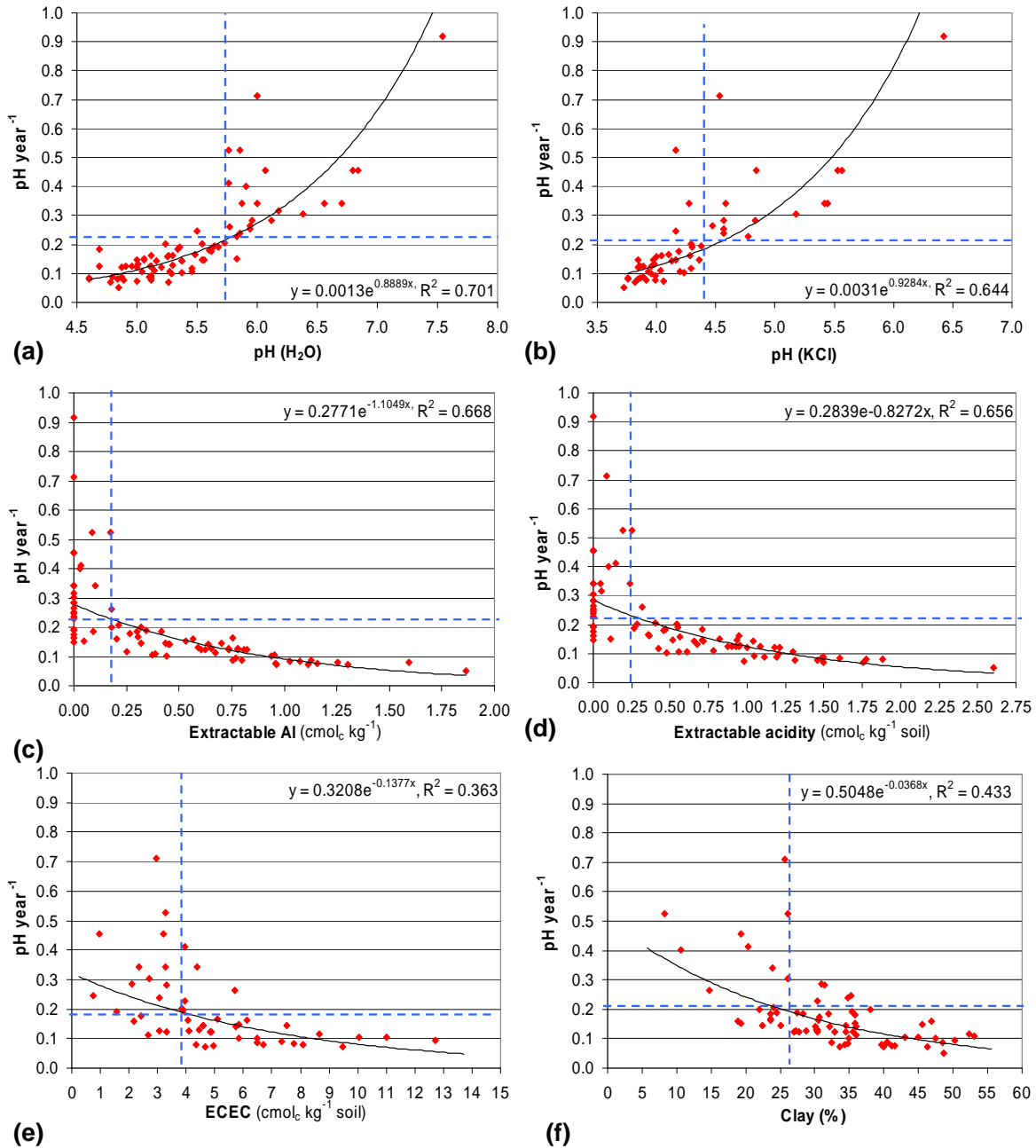


### 7.3.7 Relationship between acidification rate and selected soil properties

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 ( $\Delta$  pH unit year<sup>-1</sup>) 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 ( $\Delta \text{pH year}^{-1}$ ) and (a) soil pH (H<sub>2</sub>O), (b) pH (KCl), (c) extractable Al, (d) extractable acidity, (e) ECEC (cmol<sub>c</sub> kg<sup>-1</sup> 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 <sup>2</sup> (%)	F	Critical value
Soil pH (H <sub>2</sub> O)	57.72	102.39 <sup>***</sup>	5.73
Soil pH (KCl)	40.86	53.21 <sup>***</sup>	4.45
Extractable Al	47.48	69.60 <sup>***</sup>	0.180 cmol <sub>c</sub> kg soil <sup>-1</sup>
Extractable acidity	47.92	70.84 <sup>***</sup>	0.253 cmol <sub>c</sub> kg soil <sup>-1</sup>
ECEC	43.63	38.06 <sup>***</sup>	3.29 cmol <sub>c</sub> kg soil <sup>-1</sup>
Clay	29.20	28.45 <sup>***</sup>	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<sub>2</sub>O) 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<sub>2</sub>O) 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<sub>c</sub> kg<sup>-1</sup> 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<sup>3+</sup> + H<sup>+</sup> + Ca<sup>2+</sup> + Mg<sup>2+</sup> + K<sup>+</sup> + Na<sup>+</sup>), is the highest when the ECEC value drops below 3.29 cmol<sub>c</sub> kg<sup>-1</sup> 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<sub>2</sub>O) 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<sup>+</sup> ha<sup>-1</sup> year<sup>-1</sup>. The lime required to balance the net acid production load to 250 mm depth was between 97 and 527 kg CaCO<sub>3</sub> ha<sup>-1</sup> year<sup>-1</sup>, with a mean of 190 kg CaCO<sub>3</sub> ha<sup>-1</sup> year<sup>-1</sup> 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  $\text{CaCO}_3 \text{ year}^{-1}$  (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.