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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 $\text{cmol}_c\ \text{kg}^{-1}$ 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.