

Persistent improvements in the structure and hydraulic conductivity of a Ferrosol due to liming

J. M. Kirkham^{A,B}, B. A. Rowe^A, and R. B. Doyle^A

^ASchool of Agricultural Science & Tasmanian Institute of Agricultural Research,
University of Tasmania, Private Bag 98, Hobart, Tas. 7005, Australia.

^BCorresponding author. Email: james.kirkham@utas.edu.au

Abstract. Changes in the soil structure and hydraulic conductivity of an Acidic Red Ferrosol were measured in a long-term (1968–2003) fertiliser experiment on pasture in north-western Tasmania, Australia. Studies were initiated following observations of both softer soil surface and cracking on plots that had received 15 t/ha of ground agricultural limestone. Liming decreased penetration resistance and increased hydraulic conductivity. These structural improvements were associated with increased mean dry aggregate size, a small increase in wet aggregate stability, higher exchangeable calcium levels, and increased plant growth, but a 9% decrease in total soil organic carbon in the surface 50 mm. This decrease in organic carbon was not associated with deterioration in soil structure, as may have been anticipated. This was probably because total organic C was still 82 g/kg on unlimed plots. Decreases in soil penetration resistance due to liming increased the likelihood of pugging from livestock but may improve ease of tillage.

This research demonstrates that liming can improve the structure of a well-aggregated Ferrosol as well as its previously reported effects of increasing soil pH and yields of pasture and barley despite decreasing organic C.

Additional keywords: lime, calcium, soil structure, aggregation, porosity, organic C.

Introduction

Ground agricultural limestone (total 15 t/ha) applied to the surface of a well-fertilised pasture growing on a Ferrosol in cool temperate Tasmania decreased penetrometer resistance in the surface 150 mm of the profile (Rowe and Johnson 1989) 10 years after the final application of ground agricultural limestone (FAL), indicating improved soil structure in this soil type, which is widely recognised for its strong and robust structure. This structural improvement is in contrast to the more common use of gypsum and agricultural limestone for structural improvements on soils with poor structure, especially resulting from sodicity (Rengasamy and Olsson 1991).

Soil improvements due to liming of a non-sodic soil have been previously reported, with lime application increasing friability, reducing power required for tillage, and decreasing the number of days between rain and when the land could be worked (Gardner and Garner 1953).

Liming at this site has been shown to increase soil pH and decrease exchangeable aluminium in the top 300 mm of the profile to levels below that considered toxic to root growth, but differences in pasture root dry matter were not detected (9 years after FAL) (Rowe and Johnson 1988). Subsequently (12 years after FAL), liming did not increase the plant-available water content of the soil to a direct-drilled barley crop despite barley being susceptible to aluminium toxicity and liming increasing barley herbage and grain yield (Rowe and Johnson 1995).

Due to previous reports at the same site of increased yield, decreased penetration resistance, and a 'softer feel' to limed plots, soil physical and chemical properties were subsequently

measured to further quantify changes in soil structure and factors associated with structural change due to liming. These results and their implications are presented in this paper.

Materials and methods

Effects of surface applied, agricultural limestone were evaluated in the presence and absence of molybdenum (Mo) using a 2 by 2 factorial design on an established pasture at the Elliott Research Station in north-western Tasmania (41°5'S, 145°46'E). The limed plots received a total of 15 t/ha of commercial grade agricultural limestone applied in 6 separate applications of 2.5 t/ha applied in 1968 and 1971–75. Sodium molybdate was applied in 1968, 1974, 1980, 1984, 1989, 1994, 1998, and 2002. The treatments also received basal annual applications of superphosphate (250 kg/ha) and muriate of potash (125 kg/ha). The neutralising value (95%) and particle size analysis of the agricultural limestone was recorded by Rowe and Johnson (1988), while Conyers *et al.* (1996) described its relative field performance.

The soil is an Acidic, Mesotrophic, Red Ferrosol; medium, non-gravelly, clay loamy/clayey, very deep; (Isbell 1996), pH 5.5 (1 : 5 soil : water) in the surface 75 mm. The site receives a mean annual rainfall of 1200 mm with about 40% falling in winter.

Clay mineralogy

Soil samples were collected from the 50–150 mm depths of a limed and an unlimed plot that were contiguous. Mineralogy of whole soil and clay fractions was determined on randomly oriented samples on an automated Philips X-ray diffractometer

with Cu radiation and a graphite monochromator. Semi-quantitative analysis by peak height was used to calculate mineral abundances.

Penetrometer resistance

A 'Rimik' cone penetrometer was used to record soil strength to a depth of 450 mm in 1985 and 1999 and to a depth of 600 mm in 2002 and 2003. Recordings were made at 6 positions in each plot during a 24-h period 2 days after the soil was brought to field capacity by either rainfall or irrigation. Mean values for depth increments of 45 mm were then calculated.

Dry aggregate size distribution

In 2003, a sample of 200–300 g, from 0–50, 50–150, and 150–300 mm, was oven-dried at 107°C and placed on a nest of 6 sieves of apertures 0.25, 0.5, 1, 2, 4, and 8 mm. A pan was placed at the base to catch aggregates <0.25 mm in diameter. Samples were then shaken for 10 s on an Endecott test sieve shaker (Model EF11); the weights of aggregates collected on the pan and each sieve were recorded and the percentage distribution of aggregates was calculated.

Wet aggregate stability

In 2002, duplicate soil samples from the surface 150 mm were collected from each plot, crumbled, and air-dried. A 50-g sample of soil aggregates >4 mm was placed on a nest of sieves of apertures 0.125, 0.25, 0.5, 1, 2, and 4 mm, immersed in water, and then moved mechanically up and down for 15 min (Gradwell and Birrell 1979). Aggregates retained on each of the sieves were then dried at 105°C and weighed, and percentage distribution of aggregates was calculated by mass balance.

In 2003, 100 g of air-dry aggregates from 0–50, 50–150, and 150–300 mm was dry-sieved to collect a size range from 2.00 to 4.75 mm and then pre-wetted with a fine spray of tap water and left to soak for 5 min. The sample was then placed on a nest of sieves of apertures 0.25 and 2.00 mm and immersed in water and moved mechanically up and down for 15 min (Baver *et al.* 1972). Aggregates retained on each sieve were then dried at 105°C and weighed and the distribution of aggregates was calculated by mass balance.

Hydraulic conductivity

Saturated hydraulic conductivity was determined using a ponded disc permeameter (10 mm head) at 2 positions in each plot on

30 January 1995 using a 200-mm-diameter disc permeameter (White and Perroux 1989).

Hydraulic conductivity was determined *in situ* at 4 positions in each plot on 1 July 2003 using a tension disc permeameter based on the design described by McKenzie and Cresswell (2002). Two disc permeameters were used by a single operator simultaneously using the audio tape method (McKenzie and Cresswell 2002). Infiltration rate was recorded at 4 tensions (–10, –4, –3, and –2 kPa) to indicate water conductance of different pore sizes.

Exchangeable calcium

In 1984, exchangeable calcium was determined at depths of 0–50, 50–100, 100–150, 150–225, and 225–300 mm by atomic absorption spectrophotometry after leaching with 0.0125 mol/L of barium chloride (Bradley *et al.* 1983).

In 2003, exchangeable calcium was determined at depths of 0–50, 50–150, and 150–300 mm by atomic absorption spectrophotometry after extraction of soil in a 1 : 20 solution of 0.5 mol/L of magnesium chloride for 16 h using a modification of the 15 F1 method of Rayment and Higginson (1992).

Total organic carbon and total nitrogen

Air-dry soil samples from depths of 0–50, 50–150, and 150–300 mm were ground to pass a 0.5 mm sieve and analysed for total C and total N using a LECO CNS analyser (Wang *et al.* 1996).

Statistical analysis

Statistical analysis of data sets was by analysis of variance in which the treatment sum of squares was partitioned so the main effects and their interactions could be tested using the *F* ratio (MSE 10 d.f.). A separate analysis was conducted for each attribute at each depth.

Results

No significant interactions between limestone and molybdenum treatments were recorded; consequently, only mean values for the limestone treatments are reported below.

Cracking

Observations of cracking on limed plots were made in January 2003 when the soil was dry (Fig. 1). The cracks which

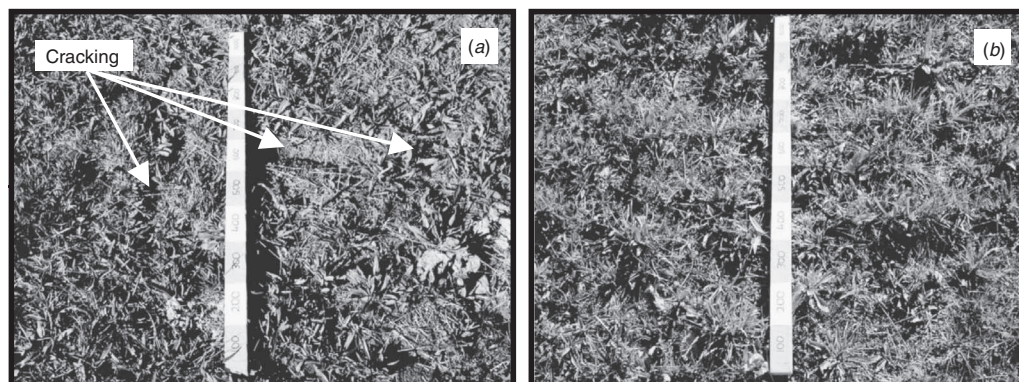


Fig. 1. (a) The presence of cracks surrounding columns of soil with a cross-section of approximately 300 mm on a limed plot compared with (b) their absence on an unlimed plot. The cracks are wide enough to insert the palm of a hand.

were 20–30 mm wide at the surface and at least 300 mm deep surrounded columns of soil with a cross section of approximately 300 mm. No cracking was observed on unlimed plots.

Clay mineralogy

The clay mineralogies of whole soil and clay components were identical for limed and unlimed soil samples. Clay samples contained halloysite (60%), hematite (15%), goethite (10%), gibbsite (5%), smectite (5%), and quartz (5%).

Penetrometer

Effects of liming on soil penetration resistance in 1985, 1999, 2002, and 2003 (10, 24, 27, and 28 years after FAL, respectively) are shown in Fig. 2.

Significant differences were only recorded at depths in the surface 300 mm and they only occurred when penetration resistance on the limed plots was less than on unlimed plots.

In 1985 differences were restricted to the surface 150 mm (Fig. 2a), whereas 14 years later (1999), effects were detected to the 300 mm level (Fig. 2b). Three years later (2002), following a pugging event, there was no significant difference between treatments, except at a depth of 180 mm (Fig. 2c). However, 18 months later (2003) resistance had again declined on the limed plots with significant differences recorded between 100 and 250 mm (Fig. 2d).

Dry aggregate size distribution

The effect of liming on dry aggregate size distribution in 2003 (28 years after FAL) is shown in Fig. 3. Liming significantly increased the percentage of coarser aggregates in the surface 150 mm but not below this level. In the surface 50 mm, there was a statistically significant increase in aggregates coarser than 4 mm at the expense of aggregates retained on sieves 1 mm and finer (Fig. 3a). Similarly, in the 50–150 mm depth, there was an increase in aggregates retained on 2- and 4-mm sieves at the expense of aggregates retained on sieves 0.5 mm and finer (Fig. 3b).

Wet aggregate stability

Liming increased aggregates retained on the 4-mm sieve from 83.6 to 93.0% ($P < 0.001$) with a consequent decrease in finer aggregates when measured in 2002 (27 years after FAL).

Liming did not significantly affect aggregate stability in the surface 50 mm ($P > 0.05$), with 86.5% of the aggregates retained on the 2-mm sieve when measured in 2003 (28 years after FAL). In the 50–150 mm depth, liming produced a very small but significant reduction from 17.9% to 16.3% in aggregates finer than 0.25 mm with no significant difference in aggregates coarser than 0.25 and 2 mm. However, in the 150–300 mm depth, liming significantly ($P < 0.05$) increased aggregates retained on the 2-mm sieve from 66.5% to 72.5% at the expense of aggregates in the 0.25–2 mm size range.

Hydraulic conductivity

Liming doubled ($P < 0.05$) saturated hydraulic conductivity of the soil from 260 to 520 mm/h when measured in 1995 (20 years after FAL).

Liming significantly increased hydraulic conductivity ($P < 0.05$) at tensions of -10 and -3 kPa compared with

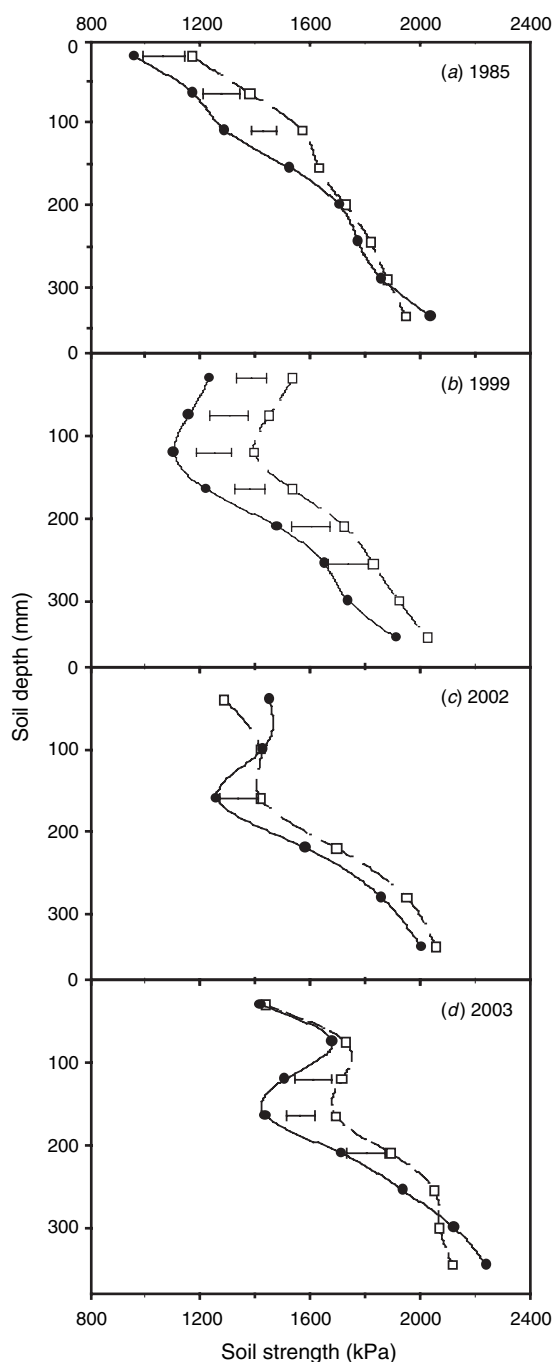


Fig. 2. Soil penetrometer resistance (kPa) at field capacity in (a) 1985 (Rowe and Johnson 1989), (b) 1999, (c) 2001, and (d) 2003 on limed (●) and unlimed plots (□). Horizontal bars represent L.S.D. values at $P = 0.05$. Absence of a horizontal bar indicates that there was no significant difference ($P > 0.05$).

unlimed treatments (Fig. 4) when measured in 2003 (28 years after FAL). The same trend was observed at tensions of -4 and -2 kPa but differences were not significant ($P > 0.05$).

These increases in hydraulic conductivity at saturation and low tension indicate an increase in medium and coarser pore sizes (Kohnke 1968).

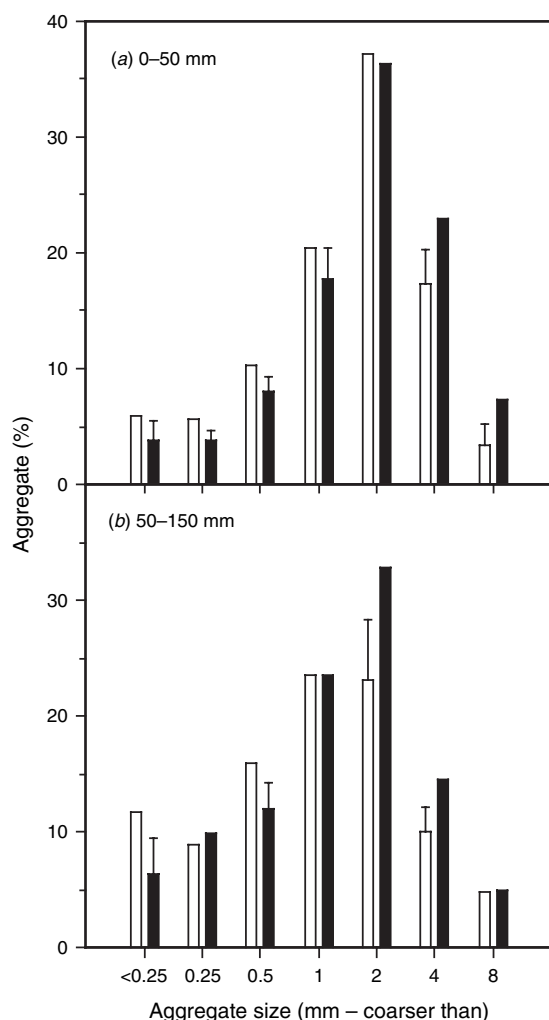


Fig. 3. The distribution of dry aggregates in 2003 on limed (■) and unlimed plots (□) in the (a) surface 50 mm and (b) 50–150 mm depth. The vertical bars represent l.s.d. values at $P=0.05$. Absence of a vertical bar indicates that there was no significant difference ($P > 0.05$).

Exchangeable calcium

Liming significantly ($P < 0.05$) increased exchangeable calcium (BaCl_2) at all 5 depths in the surface 300 mm (Fig. 5a) when measured in 1984 (9 years after FAL). Similarly, liming significantly ($P < 0.05$) increased exchangeable calcium (MgCl_2) at the 3 depths in the surface 300 mm (Fig. 5b) when measured in 2003 (28 years after FAL).

Total organic carbon and total nitrogen

In the surface 50 mm, organic C levels were significantly lower ($P < 0.05$) in limed plots (82.0 g/kg) than the unlimed treatment (90.3 g/kg) when measured in 2003 (28 years after FAL). Similarly, total N in the surface 50 mm was significantly lower ($P < 0.05$) on limed plots (7.3 g/kg), compared with 8.0 g/kg in unlimed plots ($P < 0.05$). No significant difference ($P > 0.05$) in C or N levels was measured at 50–150 or 150–300 mm sample depths; mean organic C levels were 59.4 and 42.9 g/kg at these depths, respectively. Liming did not significantly affect the C : N

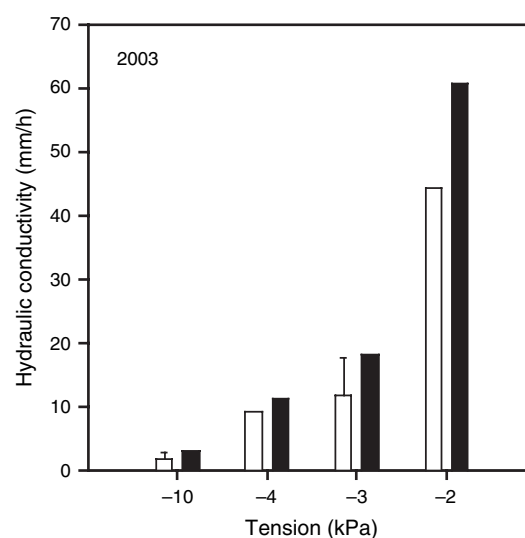


Fig. 4. The hydraulic conductivity at tensions of -10 , -4 , -3 , and -2 kPa on limed on limed (■) and unlimed plots (□) in 2003. Vertical bars represent l.s.d. values at $P=0.05$. Absence of a vertical bar indicates that there was no significant difference ($P > 0.05$).

ratio at any depth. Mean values were 11.22 in the surface 50 mm, 11.39 in the 50–150 mm, and 12.08 in the 150–300 mm level.

Discussion and conclusions

The dissolution of agricultural limestone (15 t/ha) applied to the surface of pasture and subsequent leaching of calcium ions through the profile to a depth of at least 300 mm improved soil physical characteristics of a Red Ferrosol 10 to 28 years after FAL. These persistent long-term improvements in soil structure were measured in terms of increased soil aggregate size and stability, a doubling of saturated hydraulic conductivity, more and larger pore sizes (Kohnke 1968), and decreased soil penetration resistance in the surface 300 mm.

We argue that the increases in soil aggregate size and stability result directly from physico-chemical changes in the soil associated with liming rather than from increases in soil organic C (Haynes and Naidu 1998). The improved aggregation resulted in increased porosity and decreased penetration resistance.

The significant 9.2% reduction of total organic C in the surface 50 mm measured 28 years after FAL was consistent with the slightly smaller reduction of 5.5% 9 years after FAL (Rowe and Johnson 1989). Reductions in organic C have also been recorded in the surface of other limed soils (Chan and Heenan 1998) and this has been attributed to increased microbiological activity and increased mineralisation of organic C (Barrow 1965) associated with higher soil pH. Surface soil structure was not detrimentally affected despite a reduction in organic C levels and this is probably due to high levels of C (82.0 g/kg) still remaining. This is consistent with the report that organic C was not positively correlated with aggregate stability and may not be a good structural indicator in Red Ferrosols (Oliver 1992).

The reduction in soil organic C levels in the surface 50 mm and negligible differences deeper in the profile were contrary to

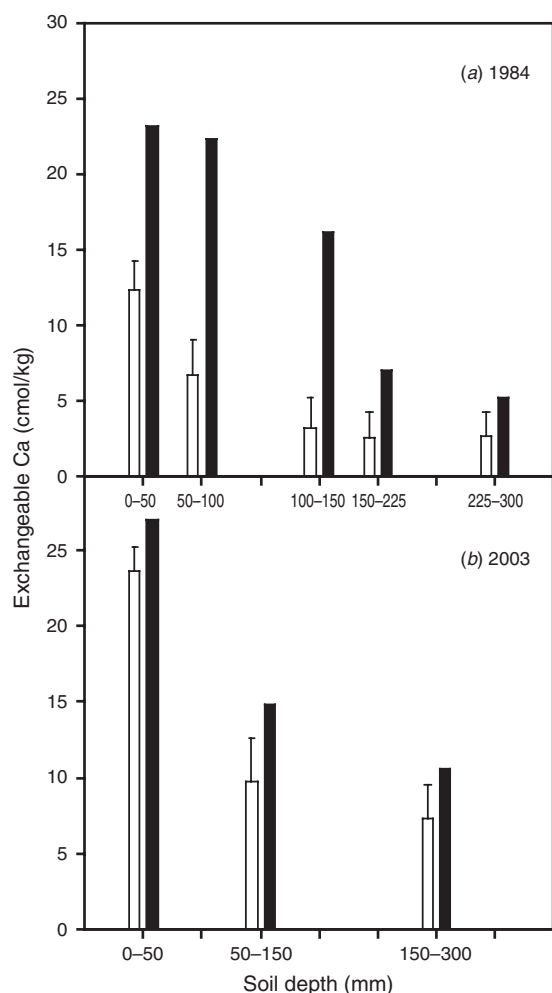


Fig. 5. The exchangeable calcium on limed (■) and unlimed plots (□) when extracted with BaCl_2 in (a) 1984 and MgCl_2 (b) 2003. Vertical bars represent L.S.D. values at $P = 0.05$. Absence of a vertical bar indicates that there was no significant difference ($P > 0.05$).

the expectation that organic matter would have increased as a result of greater plant growth due to liming (Haynes and Naidu 1998). In this experiment, substantial increases in herbage mass of pasture (Rowe 1982; Rowe and Johnson 1988) and barley (Rowe and Johnson 1995) due to liming have been recorded, but common grazing of plots mainly by sheep and consequent return of faeces evenly across the experiment would have reduced these differences. However, a concomitant increase in root growth associated with the increased herbage yields on limed plots might have been expected to increase soil organic C levels throughout the upper profile. Since there was no net accumulation of carbon, we conclude that either organic C did not increase on limed plots or, more probably, organic C accumulation is balanced by mineralisation at depths below 50 mm.

We argue that the increases in aggregate size and stability demonstrated in this experiment is a result of the flocculating affect of calcium ions on humic and clay materials. Calcium ions in soil aid aggregation by forming bridges that link functional humic groups into macro modules (Munee and Oades 1989).

They also link clay platelets to form clay domains and link these to humic materials and oxyhydroxides (Emerson 1959; Munee and Oades 1989). Rowe and Johnson (1995) have shown these soils to have high levels of exchangeable aluminium, which when displaced in acid soils by added calcium ions can form positively charged hydroxy-aluminium polymers (Haynes 1984). These polymers can strongly sorb on to clay surfaces and act as a mechanism of aggregation (Haynes and Naidu 1998).

The cracking in the limed treatments is likely to be related to changes in the interlayer cations of the smectite clays from aluminium hydroxides, which form interlayer polymers preventing shrinkage, to calcium ions, which would allow up to 30% shrinkage of the 5% smectite clay fraction (J. Churchman, pers. comm.; Dixon and Jackson 1962; Barnhisel 1977). Also, Hallaire (1985) has shown how dense, thin cracking in clayey soils can partially collapse and create a network of wider cracks on drying. A combination of these 2 mechanisms may explain the coarse cracking pattern so evident in the limed treatments despite the low amount of reactive smectite clay.

The coarser and stronger aggregation (>2 mm) measured in the surface 150 mm, induced by the above-mentioned mechanisms, was possibly associated with increased abundance of coarse pores (≥ 0.3 mm) in limed treatments. This resulted in improved hydraulic conductivity at the soil surface. The positive relationship between increases in coarse aggregates and increased hydraulic conductivity has been previously reported (Lado *et al.* 2004).

The reduction in penetration resistance as a result of liming is consistent with previous reports that heavy applications of lime can improve field texture of heavy land and this effect 'is often so great as to be detectable by its tread and can be noticed by skilled person even if blindfolded' (Gardner and Garner 1953). This reduction appears to move progressively from the surface (Fig. 2a) to deeper in the profile (Fig. 2b) as calcium ions also move and react with soil over time. There is, however, an apparent delay between the movement of calcium ions (Fig. 4a) and reduction in penetration resistance (Fig. 2a).

Lime application and its consequent reduction in penetration resistance made the soil more susceptible to pugging under wet conditions. Differences in soil penetration resistance between limed and unlimed soils (Fig. 2a and b) were nullified after the plots were grazed under wet conditions and severe pugging was observed on limed plots only (Fig. 2c). However, within 18 months, significantly lower penetration resistances were again recorded on limed plots, indicating that soil structure was improving (Fig. 2d).

The improvements in soil structure resulting from liming are of real importance to sustainable use of Red Ferrosols. In particular, increased aggregate size and stability together with improved hydraulic conductivity should result in decreased potential for water erosion and sedimentation of dams and streams, particularly when these soils are used for intensive cropping. Furthermore, the reduction in penetration resistance indicates that limed soils may provide easier root growth, are more friable, and require less energy to work. The reduction in organic C in the surface did not have a detrimental affect on structure; however, it may have long-term environmental implications as liming led to a loss of approximately 4.5 t/ha of C.

Further studies are required to confirm the benefits of lime application on Ferrosols under cropping, as they have been found to have up to 30% less organic C than the same soils under pasture (Sparrow *et al.* 1999), particularly as Cotching *et al.* (2002) have presented correlations for intensively cropped and eroded Ferrosols that are both consistent and inconsistent with our results.

Acknowledgments

This long-term experiment was made possible by the ongoing interest and cooperation of the managers and staff of the Elliott Research and Demonstration Station and the professional and technical commitment of Mr D. E. Johnson and Mr D. Butler of the Tasmanian Department of Primary Industry and Water during the last 30 years. The Tasmanian Institute of Agricultural Research funded summer studentships for Mr R. Baker, Dr R. Rawnsley, and Mr M. Robinson who measured hydraulic conductivity in 1995, penetration resistance in 1999, and wet aggregate stability in 2002, respectively. Dr G. Jock Churchman from the University of Adelaide provided advice on clay mineralogy. Exchangeable calcium in 1984 was determined by the Chemistry Branch, Biological and Chemical Research Institute, Rydalmere, New South Wales. Total C and total N in were determined in 2003 by the Queensland Department of Primary Industry. The soil and clay mineralogy were conducted in 2006 by Mr R. Bottrill, Mineral Resources, Tasmania.

References

- Barnhisel RI (1977) Chlorites and hydroxy interlayered vermiculite and smectite. In 'Minerals in soil environments'. (Eds JB Dixon, SB Weed, JA Kittrick, MH Milford, JL White) (Soil Science Society of America: Madison, WI)
- Barrow NJ (1965) Further investigation of the use of lime on established pastures. *Australian Journal of Experimental Agriculture and Animal Husbandry* **5**, 442–449. doi: 10.1071/EA9650442
- Baver LD, Gardner WH, Gardner WR (1972) 'Soil physics.' (John Wiley and Sons: Canada)
- Bradley J, Vimpany IA, Milham PJ, Abbott TS (1983) 'Soil Testing Service—methods and interpretation.' (Department of Agriculture: Sydney)
- Chan KY, Heenan DP (1998) Effect of lime (CaCO₃) application on soil structural stability of a red earth. *Australian Journal of Soil Research* **36**, 73–86. doi: 10.1071/S97054
- Conyers MK, Scott BJ, Fisher R, Lill W (1996) Predicting the field performance of twelve commercial liming materials from southern Australia. *Fertilizer Research* **44**, 151–161. doi: 10.1007/BF00750805
- Cotching WE, Hawkins K, Sparrow LA, McCorkell BE, Rowley W (2002) Crop yields and soil properties on eroded slopes of red ferrosols in north-west Tasmania. *Australian Journal of Soil Research* **40**, 625–642. doi: 10.1071/SR01062
- Dixon JB, Jackson ML (1962) Properties of intergradient chlorite-expandable layer silicates of soils. *Soil Science Society of America Proceedings* **26**, 358–362.
- Emerson WW (1959) The structure of soil crumbs. *Journal of Soil Science* **10**, 235–244. doi: 10.1111/j.1365-2389.1959.tb02346.x
- Gardner HW, Garner HV (1953) 'The use of lime.' (Farmer and Stock-Breeder Publications Ltd: London)
- Gradwell MW, Birrell KS (1979) Water stability of soil aggregates. N.Z. Soil Bureau, Scientific Report 10C.
- Hallaire V (1985) Evolution of crack networks during shrinkage of a clay soil under grass and winter wheat crops. In 'International Symposium on Water Movement in Heavy Clay Soils'. Wageningen, The Netherlands. pp. 49–54.
- Haynes RJ (1984) Effect of lime, silicate, and phosphate applications – on the concentrations of extractable aluminum and phosphate in a spodosol. *Soil Science* **138**, 8–14. doi: 10.1097/00010694-198407000-00002
- Haynes RJ, Naidu R (1998) Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems* **51**, 123–137. doi: 10.1023/A:1009738307837
- Isbell RF (1996) 'The Australian Soil Classification.' (CSIRO Publishing: Collingwood, Vic.)
- Kohnke H (1968) 'Soil physics.' (McGraw-Hill Inc.: New York)
- Lado M, Paz A, Ben-Hur M (2004) Organic matter and aggregate size interactions in infiltration, seal formation, and soil loss. *Soil Science Society of America Journal* **68**, 935–942.
- McKenzie NJ, Cresswell HP (2002) Selecting a method for hydraulic conductivity. In 'Soil physical measurement and interpretation for land evaluation: a laboratory handbook'. (Eds N McKenzie, K Coughlan, H Cresswell) pp. 90–107. (CSIRO Publishing: Collingwood, Vic.)
- Munier M, Oades JM (1989) The role of Ca-organic interactions in soil aggregate stability. III. Mechanisms and models. *Australian Journal of Soil Research* **27**, 389–399. doi: 10.1071/SR9890389
- Oliver C (1992) The relationship between soil organic matter and aggregate stability of intensively cropped soils of northern Tasmania. BAgSc(Hons) thesis, University of Tasmania, Australia.
- Rayment GE, Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods.' (Inkata Press Pty Ltd: Melbourne, Vic.)
- Rengasamy P, Olsson KA (1991) Sodicity and soil structure. *Australian Journal of Soil Research* **29**, 935–952. doi: 10.1071/SR9910935
- Rowe BA (1982) Effects of limestone on pasture yields and the pH of two krasnozems in north-western Tasmania. *Australian Journal of Experimental Agriculture and Animal Husbandry* **22**, 100–105.
- Rowe BA, Johnson DE (1988) Residual effects of limestone on pasture yields, soil pH and soil aluminium in a krasnozem in north-western Tasmania. *Australian Journal of Experimental Agriculture* **28**, 571–576. doi: 10.1071/EA9880571
- Rowe BA, Johnson DE (1989) Liming reduces the soil strength of a krasnozem. In 'Proceedings of the 5th Australian Agronomy Conference'. Perth, West Aust. p. 574. (Australian Society of Agronomy: Parkville, Vic.)
- Rowe BA, Johnson DE (1995) Residual benefits of limestone and superphosphate on barley yields and soil-water deficits on a krasnozem in north-western Tasmania. *Australian Journal of Experimental Agriculture* **35**, 611–617. doi: 10.1071/EA9950611
- Sparrow LA, Cotching WE, Cooper J, Rowley W (1999) Attributes of Tasmanian ferrosols under different agricultural management. *Australian Journal of Soil Research* **37**, 603–622. doi: 10.1071/SR98108
- Wang XJ, Smethurst PJ, Herbert AM (1996) Relationships between three measures of organic matter or carbon in soils of eucalypt plantations in Tasmania. *Australian Journal of Soil Research* **34**, 545–553. doi: 10.1071/SR9960545
- White I, Perroux KM (1989) Estimation of unsaturated hydraulic conductivity from field sorptivity measurements. *Soil Science Society of America Journal* **53**, 324–329.

Manuscript received 30 November 2006, accepted 23 March 2007