A COMPENDIUM OF THE EFFECTS OF LIMING MATERIALS ON CROP, PASTURE AND SOIL CHARACTERISTICS IN TASMANIA, AUSTRALIA, FROM 1940 TO 2020

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(with four figures, three tables and four plates)

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Crushed agricultural limestone and dolomite are used primarily to increase soil pH ($pH_{w)}$ with its consequent effects on plant nutrient availability and successful introduction of *Rhizobium* spp. to ensure effective nodulation and nitrogen fixation by pasture and crop legumes. They have also been shown to correct calcium deficiency and, in the case of dolomite, magnesium deficiency as well. Positive effects of liming recorded in Tasmania include increasing phosphorus availability, correcting molybdenum deficiency, ameliorating toxicities of manganese and aluminium, reducing crop cadmium concentrations in root crops, reducing phosphorus leaching, improving soil structure and negating soil acidification processes. Negative effects of liming that have been reported include inducing boron deficiency and encouraging plant disease. Options for future research are canvassed.
Key Words: calcium, magnesium, pH, nodulation, nitrogen fixation, phosphorus, molybdenum, manganese, aluminium, cadmium, boron, deficiency, toxicity, plant disease.

INTRODUCTION

Ground limestone and dolomite have been widely used in Tasmanian agriculture to neutralise natural acidity of acid soils as well as the acidifying effects of nitrogen fertilisers and atmospheric sulphur from marine and industrial sources. Burnt limestone products have been mixed with superphosphate to neutralise acidity of superphosphate as well as in mixtures with copper and sulphur to produce fungicides (Rowe 2023).

Annual production of agricultural liming materials in Tasmania increased from four kilotonnes (kt) in 1940 to 207 kt in 2001 before declining to an average of 145 kt between 2006 and 2020. Sources of various liming materials, their cost, transport, quality control and current usage have been reviewed (Rowe 2023). Soil types are as described in the original papers. Their acidity and distribution in Tasmania are as described (Nicolls & Dimmock 1965, Rowe 2023) and their putative attribution to the soil orders of the Australian Soil Classification Scheme (Isbell 2002) are shown in brackets (Cotching *et al.* 2009, Rowe 2023). This paper should be read in conjunction with its companion paper (Rowe 2023).

Prior to 1970, research concentrated primarily on the immediate effects of liming at rates up to 2.5 t/ha on growth of pasture legumes and annual vegetable and fodder crops. There are no reported investigations of liming effects on soil pH_w apart from establishing target pH_w values to ensure plant establishment and growth.

Around the mid-1970s, problems associated with soil acidification were becoming recognised around Australia mainly due to occurrences of manganese and aluminium toxicity. The latter was of particular concern where acidification occurred deeper in soil profiles (Bromfield *et al.* 1983) where it was difficult to remedy. Nutrient deficiencies and toxicities that are corrected or induced by liming are often identified by visual symptoms on plant leaves or fruit (Wallace 1943, Millikan 1953, 1958, Wallace 1961, Grundon *et al.* 1997) and/or plant nutrient levels in leaves (Smith & Loneragan 1997) or soils (Peverill *et al.* 2001). These diagnoses are often confirmed by measuring plant responses to liming materials in glasshouse pots or field plots.

Direct effects of liming to correct calcium and magnesium deficiencies in Tasmania are reported. Furthermore, benefits and/or disadvantages of liming on yield and/or quality of pastures and crops are recorded. Underlying mechanisms associated with responses to increasing soil pH_w are reported where they were identified. Effects of liming on changes in soil profile pH_w were investigated primarily on Krasnozems (Ferrosols) in northern Tasmania.

This paper documents the many roles that liming materials play in Tasmanian agriculture. However, the review is also relevant to comparable soils in Gippsland and western Victoria in cool temperate Australia (Paton & Hosking 1970) as well as similar soils nationally and internationally.

Application rates of limestone/dolomite

Application rates of limestone/dolomite rarely exceeded 2.5 t/ha when applied to cultivated seedbeds prior to establishing pasture (McCutcheon 1989), forage crops (Lamp 1966), and vegetable or field crops. However, in some cases lower rates are drilled with the seed. Similarly, rates in excess of 2.5 t/ha were rarely applied to established pastures (Paton 1960). Despite relatively slow dissolution rates of some particles in commercial limestone/dolomite products (Stackhouse 1985, Rowe 2023) responses to liming were invariably recorded within the first growing season (≤ 6 months).

By the mid-1970s, effects of agricultural limestone at rates in excess of 2.5 t/ha were being investigated, with rates up to 15 t/ha being evaluated on pasture (Rowe 1982, Rowe & Johnson 1988), 20 t/ha on a sequence of annual crops (sugar beet, poppies and onions) (Anon 1981, Temple-Smith 1982, Temple-Smith & Laughlin 1985a, 1985b), 40 t/ha on potatoes and carrots (Sparrow *et al.* 1993a, 1993b, Sparrow & Salardini 1997) and up to 100 t/ha in preparing soils to grow French truffles (Garvey & Cooper 2004).

Calcium and magnesium deficiencies

Limestone and dolomite are sources of calcium and, in the case of dolomite, magnesium as well. Calcium and magnesium deficiency were widespread on yellow podzolic soils (Kurosols) in orcharding areas in southern Tasmania prior to the mid-1960s. However, only calcium deficiency has been reported to occur in pastures and field and vegetable crops.

Calcium deficiency

Symptoms of 'bitter pit' in apple fruit, which are attributed to calcium deficiency, have occurred in all orcharding areas of Tasmania but particularly in the Huon Valley. The cause of 'bitter pit' was investigated (Martin *et al.* 1960, Martin *et al.* 1962) and symptoms were dramatically reduced under field conditions by applications of 5–6 calcium sprays (e.g., calcium chloride or calcium nitrate at 5–8 g/l) applied from the calyx stage (Matthews & Wilson 1961, Raphael & Richards 1962). 'Bitter pit' occurred primarily in dry seasons in unirrigated orchards even where limestone had been applied in an attempt to alleviate the problem.

Isolated cases of calcium deficiency have also been reported in peaches (Ward 1955). 'Withertop' or 'flaxwilt' in flax *Linum usitatissimum*, resulting from calcium deficiency, was recorded in 1949 in Tasmania (Sampson & Walker 1982). It is due to a temporary deficiency of calcium in flax plants induced by waterlogging of soils during the stage of rapid elongation (Millikan 1944). It is evidenced by a weakening and toppling of stems 75–100 mm from the tip of the plant causing stems to be much reduced in length. It can be avoided by heavy dressings of limestone (Millikan 1944, Wade 1949a).

Calcium deficiency in pasture and forage crop species has been reported on strongly acid coastal sandy heathland soils (Podosols) in far northwest Tasmania and on Flinders Island (Fricke 1965).

Magnesium deficiency

Reports of magnesium deficiency are even rarer than those of calcium deficiency. Magnesium deficiency symptoms were reported to occur in apples due to a physiological imbalance caused by excessive use of potassium fertilisers. This problem occurred on all soils and varieties in the Huon Valley in the late 1950s. The recommended remedy was to cease potassium applications, apply Epsom salts in 5–7 sprays from the calyx stage and to apply dolomite at 1.6 t/ha (Ward 1957, 1958).

Increased phosphorus availability due to liming

In early pot experiments, incorporation of a range of alkaline materials at rates equivalent to 2.5 t limestone/ha to the surface 12.5 mm of a lateritic podsol (Kurosol), known locally as Cressy clay loam, showed that pH_w of the surface 12.5 mm of soil needed to be raised to pH_w 7.0 for responses in both the presence and absence of applied superphosphate to be maximised. Responses were attributed to a decrease in anion exchange capacity as pH_w increased from 6.0 to 7.0 and a consequent increase in availability of phosphorus (Stephens *et al.* 1942). Subsequent research showed that at least part of the yield response of white clover due to liming on this soil resulted from the release of molybdenum as pH_w increased to a pH_w of 7.0. However, a small part of the response was still attributable to the release of phosphorus (Stephens & Oertel 1943).

Associated increases in pH_w were confined to the surface 12.5 mm of the pots indicating that whatever mechanism produced the response, it was active within this shallow layer. Subsequent research using lime and other plant nutrients applied to the surface of soil and pasture did nothing to suggest that responses were other than those associated with surface effects, at least until the 1980s when responses to heavy rates of limestone began to be reported.

About 40 years later, grain yield of nitrogen and phosphorus (50 kg P/ha) fertilised barley grown on a Krasnozem (Ferrosol)(pH_w 5.0) containing high levels (77 ppm) of bicarbonate extractable phosphorus (Colwell 1965) increased linearly by 100 kg/t of limestone applied. In the absence of applied phosphorus, limestone increased barley yield by 230 kg/t of limestone, whereas in the presence of phosphorus, the increase averaged only 100 kg/t of limestone applied. This indicates that at least part of the effect of liming is to release phosphorus (Russell 1986).

Molybdenum deficiency and the role of agricultural liming materials

Pasture legumes

Recognition that molybdenum is required in trace amounts for plant growth and nitrogen fixation (Arnon & Stout 1939) was followed in 1942 by a report of molybdenum deficiency on a South Australian ironstone soil (Anderson 1942).

Subsequently, responses to molybdenum were recorded in clovers grown in pots on an ironstone soil from near Cressy in northern Tasmania (Stephens & Oertel 1943). This soil is a lateritic podzolic soil (Kurosol) known locally as Cressy Shaley clay loam. Subsequently, Fricke (Fricke 1943, 1944, 1945a, 1945b) showed that molybdenum deficiency in pasture legumes was widespread in the Northern Midlands, northeastern and northwestern districts of Tasmania. Since then pasture (clover) responses to molybdenum were obtained in most developed areas of the state (Paton 1956a).

Later it was shown that, where responses to dressings of limestone (2.5 t/ha) were recorded on well-established clover pastures, equivalent responses were obtained with molybdenum. It was concluded that the main effect of lime on many Tasmanian soils is to increase availability of molybdenum to pasture legumes (Paton 1960). The current recommended rate of molybdenum application to legume pastures is 60 g Mo/ha, applied no more frequently than once every five years (TempleSmith & Munday 1976).

Crops legumes

Similarly to pasture legumes, molybdenum was shown to improve nitrogen fixation and growth in green peas (Wade 1952) and blue and grey peas (Tilt & Taylor 1954).

Brassica crops

It has been shown that 'whiptail' in cauliflowers, as evidenced by the reduced size, puckering, distortion of leaf blades and irregular leaf margins when grown on some acid soils, can be corrected by liming. However, 'whiptail' can be corrected by molybdenum applied mixed with superphosphate (Wade 1949a, 1949b).

Role of liming in nodulation and nitrogen fixation

Pasture legumes

A strain of *Rhizobium trifolii* was selected in 1953 from nitrogen fixing nodules growing on roots of subterranean clover (*Trifolium subterraneum* cv. Mt Barker) growing in a Podosol on the property, 'West Thorpe', on the Waterhouse Estate about 20 km east of Bridport in northeast Tasmania (Morling pers. com.). Prior to this time, available commercial strains for subterranean clover were largely ineffective. Subsequently, this strain was shown to produce effective nodules on the roots of both white clover *Trifolium repens* and subterranean clover *Trifolium subterraneum* that resulted in spectacular increases in clover growth (Paton 1957). It was subsequently designated as strain TA1.

Effective nodulation and efficient nitrogen fixation of pasture legumes using TA1 depends on introduction and survival of effective rhizobia near the germinating seed and correction of nutrient deficiencies. Successful introduction of inoculum into the soil involves both inoculum survival on the seed prior to and during sowing and then its survival in the seedbed. It usually involves adhering rhizobia in a peat inoculum to the seed using an adhesive such as Gum Arabic or Cellofas A and then applying a coating of powdered limestone, dolomite or Plastaid®(Walker 1969a, 1978, Rowe & Johnson 1985, 1990) to the surface to improve survival of rhizobia on the seed surface until sowing. The physical and chemical properties of Plastaid® are described (Rowe 2023). These coatings also protect rhizobia from acidity of fertiliser when seed and fertiliser are mixed together before sowing. Other strategies to ensure inoculum survival during sowing include sowing the seed and fertiliser from separate seed boxes or sowing with limestone alone, with basic superphosphate (50:50 limestone-superphosphate mix) or with reverted superphosphate (15:85 burnt lime-superphosphate mix) (Paton 1957, 1960).

Survival of Rhizobia in soil is dependent on soil pH_w in contact with the germinated seed. Research, predominantly on wet heathland (Podosols), swamp soils (Organosols), and Krasnozems (Ferrosols) has shown that successful nodulation and nitrogen fixation can be assured if ground limestone/dolomite is applied at rates and by methods that vary according to soil type and seedbed acidity measured in a 1:5 soil: water mixture (pH_w) or in a 1:5 soil: 0.01 M $CaCl_2$ mixture (pH_{Ca}) for virgin or newly developed soils as shown in Table 1 (McCutcheon 1989).

Target pH_w were higher on Krasnosems for each recommended rate of limestone/dolomite application rate probably because of their higher buffering capacity. On Krasnozems (Ferrosols), 2.5 t/ha was recommended to be applied and worked into the soil surface prior to sowing when pH_w was <5.2, whereas limestone drilled with seed at 250–375 kg/ha was recommended when pH_w of Krasnozems (Ferrosols) was 5.2–5.5. In contrast, on other acid soils 2.5 t/ha was recommended to be applied and worked into the soil surface prior to sowing when pHw was <4.8, whereas limestone drilled with seed at rates of 250–375 kg/ha was recommended when pHw was 4.8–5.2.

Apart from liming, the full potential of the nitrogen fixation process is dependent on correction of widespread deficiencies of phosphorus (Paton 1956a, Paton & Hosking 1970), potassium (Paton 1956b) and molybdenum (Paton 1956a), whereas copper and zinc deficiencies have limited nitrogen fixation on wet heathland/swamp soils (Podosols and Organosols) on Flinders Island, King Island and in northern Tasmania (Paton & Hosking 1970). Sulphur deficiency rarely occurs except on Podosols in north-east Tasmania (Martinick 1974) where annual contributions of sulphur from fertilisers (e.g. superphosphate) and sulphur in rainfall from maritime (Martinick 1974, Blair *et al.* 1997) and industrial sources (Martinick 1974) were insufficient to prevent sulphur deficiency. Consequently, sulphur supplementation using sulphur fortified superphosphate containing an extra 280 kg of elemental sulphur per tonne

TABLE 1 — Target pH_w measured in 1:5 soil-water or pH_{Ca} measured in 1:5 soil to 0.01 M calcium chloride suspensions to guide application rates of agricultural limestone to ensure satisfactory nodulation and nitrogen fixation of white (*Trifolium repens)* and subterranean clover (*Trifolium subterraneum*) (McCutcheon 1989).

Rate (kg/ha) of limestone/ dolomite to be applied	Krasnozems (Ferrosols) pH_w	Other soils pH_w	Virgin soils pH_{Ca}
Nil	> 5.5	> 5.2	> 4.3
250–375 Drilled with seeds	5.2–5.5	4.8–5.2	3.9–4.3
2,500 Broadcast on soil surface	< 5.2	< 4.8	< 3.9

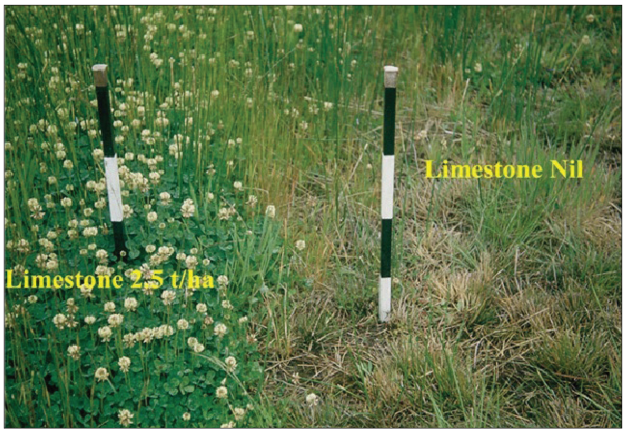

PLATE 1 — The effect of agricultural limestone broadcast at 2.5 t/ha on the surface of a Podosol (pH_w = 4.2) and worked into the surface on the establishment and growth of white clover *Trifolium repens* shown on the left of the photo compared to that on unlimed soil.

of superphosphate was warranted (Fricke 1969). Iron pyrites, as a slow-release sulphur source, was shown to be an effective sulphur source for these soils (Banath 1969) but was not used commercially.

Other pasture and crop legumes

The same principles and practices used for clovers have been applied to ensure satisfactory nodulation and nitrogen fixation in other pasture and crop legumes. Specific strains of rhizobia required to produce effective nodules on different legumes species (McCutcheon 1989) include: Rhizobia Group (RG) A is used on *Medicago* spp. including lucerne; RG – B is used on white, red, strawberry and shaftal clovers; RG – C is used on rose, cupped and crimson clovers and all subterranean clovers; RG – D is used on lotus major and birdsfoot trefoil; RG – E is used on peas, vetches, tares and faba beans; RG – F is used on beans including French, Navy and climbing beans; RG – B is used on lupins and serradella.

TABLE 2 — Target soil pH_w values for effective establishment of Lucerne (*Medicago sativa*) and a range of vegetable crops based on glasshouse and field experiments together with local observation.

Crop	Depth (mm)	Krasnozems (Ferrosols)	Reference
Lucerne		6.0	Kjar 1967
		6.0–7.0	Halpern 1966
		≤ 5.7	Anon 1982
Carrots		5.7–6.5	Walker & Walker 1970
Green beans		5.7–7.0	Walker 1969b
Onions	0–300	6.5–7.0	Walker & Cox 1970
Peas		6.0	Allen & Frappell 1961
Poppies		≥5.5	Allen & Frappell 1970

Target soil pH_w for satisfactory growth of pasture legumes and other crops

Liming and the associated increase in soil pH_w increased the establishment of pasture legumes (table 1) and yields of vegetable crops, including potatoes, and forages in Tasmania (table 2). Target soil pH_w levels to guide application rates of limestone to soils growing different species have been developed from observation of visual symptoms of toxicities, field and glasshouse experiments and experience of farmers and their advisors (table 2).

Liming and the alleviation of manganese toxicity

Manganese toxicity has been recorded in forage and vegetable brassica crops grown on Krasnozems (Ferrosols) in northern Tasmania (Wade 1961, Lamp 1966). These include chou-moellier ≅ marrow stemmed kale *Brassica oleracea* and rape *Brassica napus* as well as cauliflower *Brassica oleracea*. A similar condition in the related crops: cabbage *Brassica oleracea*, swede *Brassica napus* and fodder beet *Beta vulgaris* has been observed (Wade 1961, Lamp 1966).

On Krasnozems (Ferrosols), manganese toxicity was associated with sheet erosion that exposed subsoils that contain manganiferous concretions which release manganese at low pHw (Lamp 1965). Symptoms of manganese toxicity in chou-moellier begin to appear when leaf manganese concentrations in leaf lamina reach 900–1,000 ppm DM and become severe at 2,500 ppm, with values of 4,200–5,000 ppm recorded (Lamp 1965, Lamp 1966).

The correction of manganese toxicity and increased yield of marrow stemmed kale due to applying limestone at 2.5 t/ha was attributed to increased pH_w rather than an increase in calcium per se since calcium, supplied as gypsum at a rate equivalent to that in limestone at 2.5 t/ha, did not correct manganese toxicity or increase yield. Furthermore, where roots were split so that half the root system was grown in soil with a pHw of 4.6 and the other half in soil that had been limed to 5.8 then root growth was equivalent in both the soil of pH_w 4.6 and 5.8. Similarly, plants grown where a segment of the profile had been increased to 5.8 showed increased root growth (Lamp 1965). In circumstances where manganese toxicity is due to low pH_w (< 5.5) then 2.5 t/ha of ground agricultural limestone is recommended to correct the problem (Lamp 1966).

Tolerance of a range of crop and vegetable species, including some Tasmanian bred cultivars (see * in list below), to increasing levels (10 to 800 μM) of manganese in solution culture was investigated (Temple-Smith & Koen 1982). They found differences in tolerance to manganese can be largely attributed to differences in manganese concentration tolerated in the shoot prior to the appearance of toxicity symptoms and growth depressions. Shoot 'toxicity threshold values' (μg Mn/g DM) for various species are listed in order of increasing tolerance: *poppy was 150; Brussel sprouts 280; Proctor barley 290; *Shannon barley 340; lucerne 380; green bean 500; green pea 840; oats 1,880; sugar beet 5,980; and lupins 10,500.

Reduced phosphorus leaching due to liming

Pastures grown on an acid sandy soil (Podosol) on Flinders Island and identified as Nala Sand (Dimmock 1957) exhibited poor growth and symptoms of acute phosphorus deficiency in the absence of heavy lime applications, even when normal dressings of superphosphate were applied. The primary effects of these heavy rates of lime (up to 10 t/ha) were attributed to reduced phosphate leaching as illustrated by retention of 82% of radioactive phosphorus in the surface inch (25 mm) of limed soil compared to only 33% in unlimed soil: autoradiographs (plate 2) further highlight this effect (Paton & Loneragan 1960).

Effects of heavy rates of limestone on soil pH_w

Studies on pH_w changes in soil profiles have been incidental to effects of liming on pasture and crop yields, reduction of aluminium toxicity and cadmium uptake. These studies were primarily conducted on Krasnozems (Ferrosols). Only the targeted increase in soil pH_w to provide a suitable environment for growing French truffles extended these studies to soils other than Krasnozems (Ferrosols).

The effects of lime rates up to 15 t/ha (Rowe 1982, Rowe & Johnson 1988), 20 t/ha (Temple-Smith *et al.* 1983), 30 t/ha (Sparrow & Salardini 1997) on pH_w were measured to a depth of 300 mm. The effects of 50 and 100 t/ha were only measured to a depth of 200 mm (Garvey & Cooper 2004).

Surface application to permanent pasture on Krasnozems (Ferrosols)

Applications of limestone in six annual increments of 2.5 t/ha (total 15 t/ha) to the surface of pasture increased pH_w of the surface 75 mm of a Krasnozem (Ferrosol) by 0.1 pH_w units/t (fig. 1A) (Rowe 1982). Subsequent reaction of limestone with the soil and leaching of calcium down the profile is evidenced by the linear decline in the surface 75 mm by 0.09 pH_w units/year over the next eight years (fig. 1b) (Rowe & Johnson 1988). This linear decline is shown to be a segment of an exponential decline from 1975 to 1996 (figs 1B, 1C) (Rowe & Johnson unpublished).

The change in soil pHw (Δ pHw) with increasing soil profile depth on the unlimed and limed plots is shown for measurements recorded in 1976 (fig. 2A) and 1984 (fig. 2B). The increase in soil pHw due to liming (Δ pHw) is shown in figure 2C. The peak of the pHw increase moved from the surface in 1976 to a depth of 125 mm in 1984, a distance of 75 mm in eight years. Furthermore, significant pHw increases were recorded deeper in the profile at a depth of 225–300 mm (Rowe & Johnson 1988). Concurrently, liming significantly increased pHw-dependent cation exchange capacity (CEC) (Bradley *et al.* 1983) of the soil (cmol+/kg) (table 3) (Rowe unpublished).

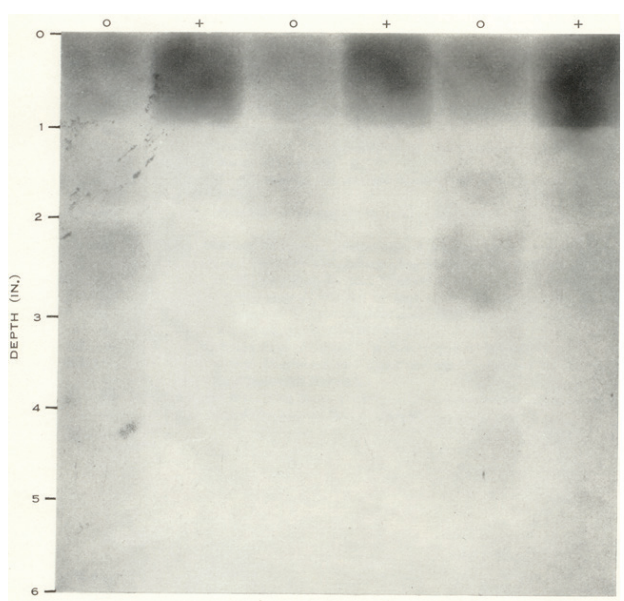

PLATE 2 — Agricultural limestone applied at 10 t/ha (+) reduced phosphorus leaching compared to no limestone (-) in a Podosol on Flinders Island (Paton & Loneragan 1960).

Effects on soil pH_w of surface application of limestone and subsequent mixing by cultivations on soil pH_w on Krasnozems (Ferrosols)

Effects of surface applications of limestone at rates of 0–20 t/ha to cultivated seedbeds on profile pH_w at two sites on Krasnozems (Ferrosols) following its incorporation using normal cultivation and sowing procedures used in establishing and harvesting a sugar beet crop (Anon 1981) and then sowing a poppy crop after harrowing and drilling inorganic fertiliser at depths up to 150 mm were measured 18 months after liming (Temple-Smith *et al.* 1983). PH_w of composite samples of 50 mm segments showed that pH_w declined from the surface 50 mm to the 50–100 mm segment with no detectable differences below 100 mm even when 20 t/ha of limestone had been applied (Temple-Smith *et al.* 1983).

However, sampling of individual segments showed that on unlimed plots pH_w had a range of 0.3–0.4 pH_w units with standard error (s.e.) of 0.08–0.14 in the three sampling depths at both sites indicating underlying micro variability of pH_w. Liming increased spatial variability as evidenced by both increased range from 0.6–2.2 pH_w units and s.e. from 0.19–0.68. This indicates that cultivations had not mixed limestone homogenously throughout the soil (Temple-Smith *et al.* 1983).

Surface application to cultivated seedbeds with major mixing cultivations

Effects of applying 30 t/ha of limestone on the soil profile pHw were measured to a depth of 300 mm two years after the limestone was broadcast to the surface (fig. 3A). Following application, the lime was mixed to a nominal depth of 150–200 mm using a rotary-hoe prior to further mixing during planting, ridging and lifting a potato crop, then followed by normal cultivations associated with sowing a poppy crop. Surface pHw were at a maximum of 7.1 in the surface 0–100 mm before gradually declining to 5.7 in the 250–300 segment. The largest pHw increases of 1.0–1.25 units were recorded in the surface 0–150 mm segment and declined to 0.2 units in the 250–300 mm depth.

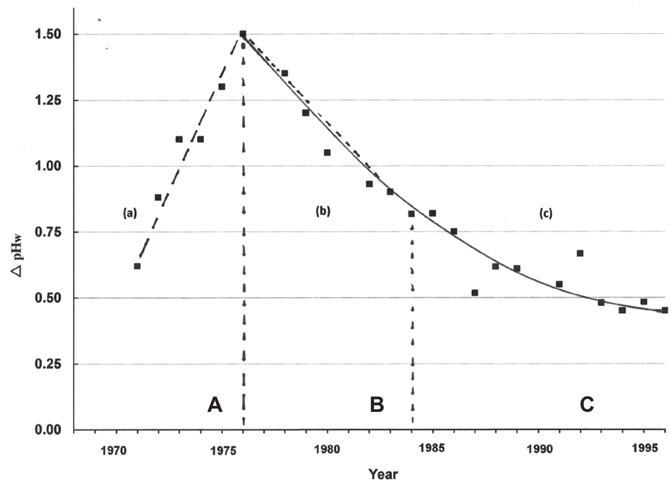

FIGURE 1 — Incremental changes (Δ pHw) in the surface 75 mm of a Krasnozem (Brown Ferrosol): (**A**) due to annual applications of limestone (L) at 2.5 t/ha between 1971 and 75 (Rowe 1982); (**B**) the subsequent decline in Δ pHw due to calcium leaching during the following eight years from 1976 to 1984 (Rowe & Johnson 1988); and (**C**) the decline in Δ pHw in the 12 years from 1984 to 1996. The curve describes the change in Δ pHw between 1975 and 1996 (Rowe & Johnson unpublished). ΔpHw = pHw of limed plots minus the pHw of the unlimed plots.

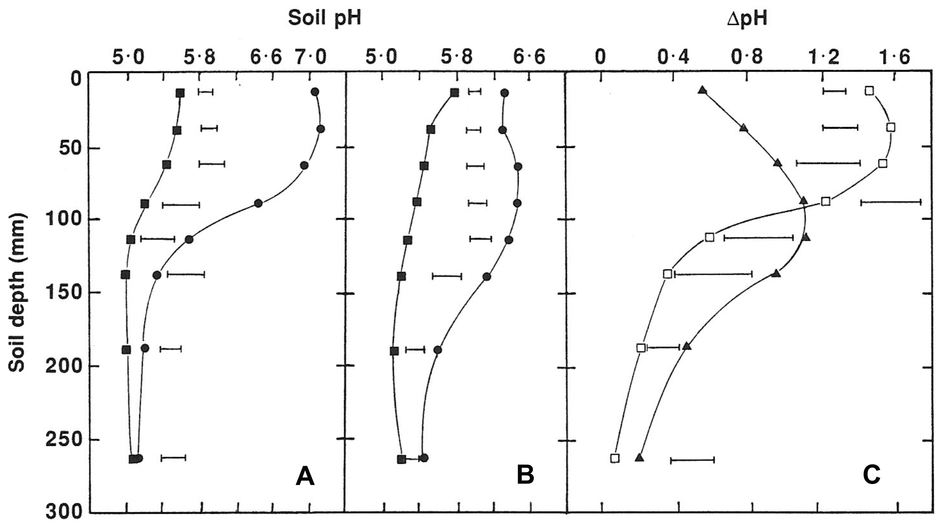

FIGURE 2 — The change in soil pHw with increasing depth of soil on limed (●) and unlimed (□) plots when measured in (**A**) 1976 and (**B**) 1984 (Rowe & Johnson 1988). (**C**) The increase in soil pH_w (ΔpH) due to the limestone applications throughout the soil profile in 1976 (□) and 1984 (▲) (1.5 and 9.3 years after the final application of limestone). The horizontal bars denote the l.s.d. (P=0.05).

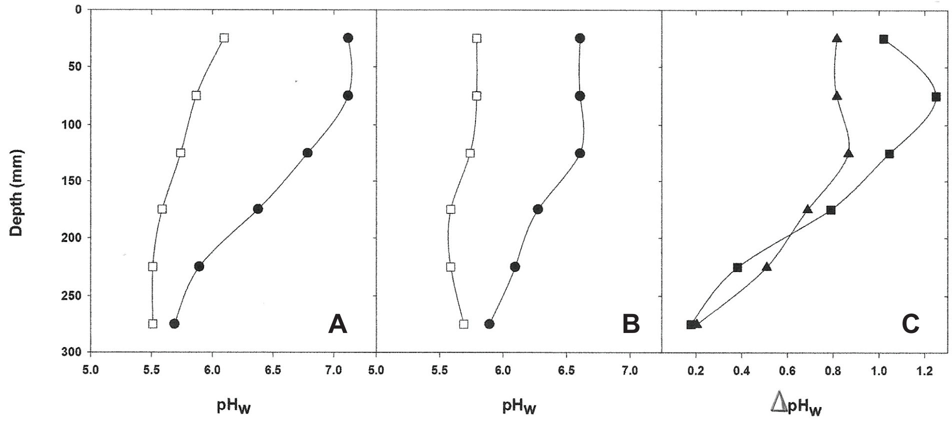

FIGURE 3 — The change in soil pHw with increasing depth of soil on limed (●) and unlimed (□) plots when measured in (**A**) 1992 and (**B**) 1995 (Sparrow & Salardini 1997). (**C**) The increase in soil pH_w (ΔpH) due to the limestone applications throughout the soil profile in 1992 (■) and 1995 (▲) (2 and 5 years after the application and incorporation of limestone).

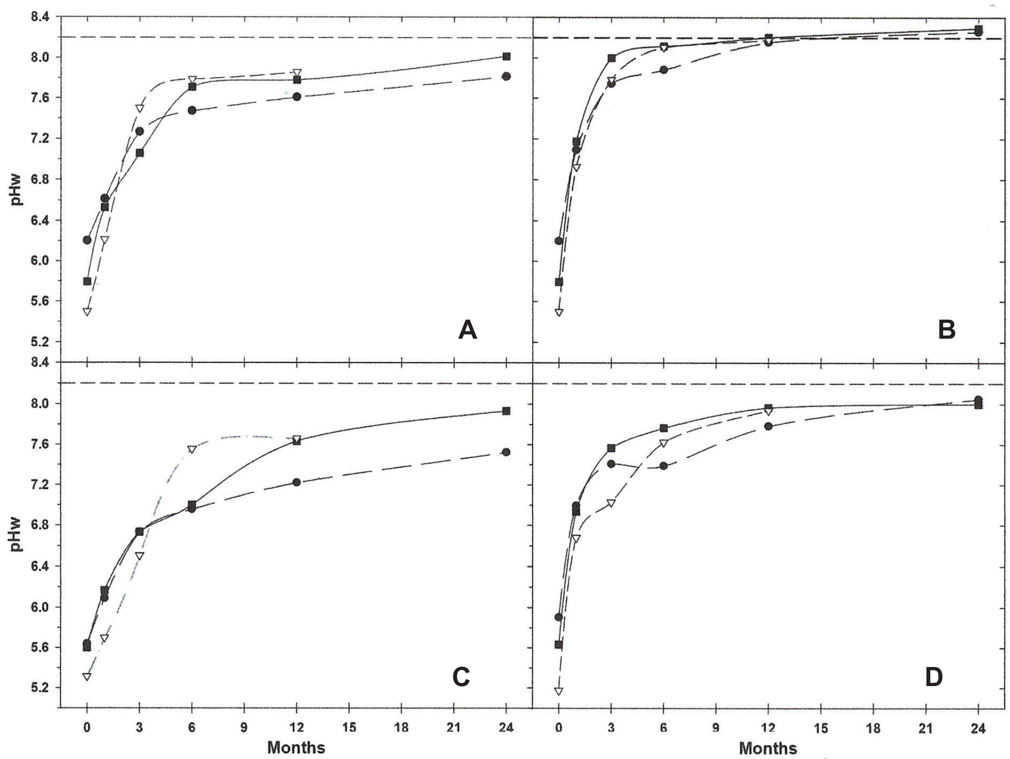

FIGURE 4 — Increases in soil pHw in a Krasnozem (Ferrosol) (●), a podzolic (▽) and an alluvial soil (■) when limestone was incorporated at 50 t/ha and measured in (**A**) the surface 50 mm and (**C**) at a depth of 100 – 200 mm. The increases in soil pH_w due to incorporating limestone at 100 t/ha in (**B**) the surface 50 mm and (**D**) at a depth of 100 to 200 mm. The horizontal dashed line represents the upper level of pH_w (8.2) in calcareous soils (Rengasamy 2022).

TABLE 3 — Increases in cation exchange capacity (cmol+/kg) (Bradley *et al.* 1983) with depth of soil profile due to liming.

Depth (mm)	Unlimed	Limed (15 t/ha)	Probability (P)
0–50	15.8	26.3	P <0.001
50–100	9.0	24.3	P <0.001
100–150	6.2	18.9	P <0.001
150–225	5.7	8.1	P < 0.01
225–300	5.3	6.6	P < 0.01

Soil profile pHw was measured again five years after the initial application of limestone following further mixing because of planting, ridging and lifting a second potato crop. At this time the surface 150 mm on limed plots had become less alkaline than when measured three years earlier (fig. 3B) with increases averaging 0.8 pH_w units in surface 150 mm (fig. 3C). Below this depth there had been very little change in Δ pH_w (fig. 3C) (Sparrow & Salardini 1997). This pattern of declining alkalinity at the surface and increasing alkalinity deeper in the profile with the passage of time is similar to that recorded in the soil profile (fig. 2) when limestone was applied to the surface of a permanent pasture (Rowe & Johnson 1988).

In the development of new trufferies, the objective is to raise pH_w above 7.5 and preferably to 7.9–8.1 to make the soils suitable to grow French truffles *Tuber melanosporum* (Garvey & Cooper 2004). Commercial limestone at rates of 50, 75 and 100 t/ha were incorporated with a disc-plough to a nominal depth of 200 mm followed by three passes of a tyned implement on a Krasnozem and an alluvial soil using limestone with a nominal particle size <2.00 mm and on a podzolic soil using limestone with a nominal particle size <1.00 mm. Increases in soil profile pH_w were measured at depths of 0–50 mm, 50–100 mm and 100–200 mm. Samples were collected prior to liming and 1, 3, 6, 12 and 24 months after liming. Replotting their data using a linear time scale revealed Mitscherlich type response curves describing increases in pHw versus sampling time for each soil and sampling depth.

Figure 4 presents a subset of this data to illustrate key features of the responses. In each instance pH_w increased rapidly from the starting pH_w to 90% or more of maximum during the first six months. Initial pH_w values ranged from 5.8–6.2 on the Krasnozem, 5.4–5.8 on the alluvium soil and 5.3–5.4 on the podzolic soil with lower pH_w values being recorded deeper in the profile. Maximum pH_w exceeded 8.0 at all depths 24 months after limestone was applied at 100 t/ha; maximum pH_w exceeded 7.8 at all other depths 24 months after limestone was applied at 75 t/ha. However, when 50 t/ha was applied, pH_w of the surface 0–50 mm exceeded 7.8, the 50–100 mm exceeded pH_w 7.6 and 100–200 mm exceeded pH_w 7.5 at 24 months after lime application. These maximum values are comparable to those recorded for calcareous soils in South Australia with a recorded range of 8.0–8.2 (Rengasamy 2022).

The conclusion from these studies is that reaction of limestone with the soil at the surface of a pasture and its movement down the profile is very slow and may well be reduced in soils where leaching of calcium ions is retarded by increases in the pH-dependent cation exchange capacity. Incorporation of limestone particles by rotary hoeing and normal cultivation methodologies primarily increases pHw of soil in the surface 100 mm, whereas deeper and more vigorous incorporation, as in growing two potato crops, did not substantially increase pH_w below 250 mm five years after application of limestone at 30 t/ha: the effects on pH_w remained primarily in the mixing zone.

Pasture yield increases due to heavy rates of limestone

Limestone applications totalling 7.5–15.0 t/ha significantly increased pasture dry matter yields from permanent, unirrigated ryegrass-white clover pasture (two sites) in more than half the harvests in summer, autumn and early spring, but not in late spring. These increases, which range from 200–1,200 kg/ha, occurred when feed supplies often restrict production from dairy herds grazing dryland pasture in north-western Tasmania. Significantly, these increases were not due to an increase in molybdenum availability associated with increases in soil pH_w (Rowe 1982).

At one of the above sites, it was shown that residual effects of having applied limestone at 15 t/ha increased annual dry matter production (DM) by 0.5–1.7 t DM/ha for at least nine years after the final application of limestone. The largest seasonal dry matter increases of 0.4–0.7 t DM/ha were recorded in autumn. It was calculated that costs of applying limestone at rates up to 15 t/ha at the then cost of $30/t would be repaid at an effective interest rate of 10% per annum within 12 years (Rowe & Johnson 1988).

Effects of limestone rates (0–10 t/ha) were investigated on established dairy pastures between 1992 and 1996, a period of three and a half years, on soils that included yellow podzolics in the Deloraine region, podzols, an acid peat and a silty clay loam in the Circular Head region around Smithton as well a site on a Krasnozem at Elliott (Freeman 1996):

(i) The three yellow podzolics (Kurosols) were very acid in the surface 75 mm (pH_w 4.7–4.9). However, the onset of significant yield increases, which occurred either 1.5, 2.5 or 3.5 years after treatments were applied, were related to the pHw in the 76–130 mm (pH_w 4.5–5.0) with the earlier response occurring where pHw was more acid deeper in the profile.

(ii) The three podzols (Podosols) had pH_w in the range 5.8–6.3 in the surface 75 mm but a bigger range in the 76–130 mm depth (pH_w 4.6–5.9). A marked increase in yield was only measured at one site which had pH_w of 5.8 in the surface 75 mm but a much lower pH_w of 4.6 in the 76–130 mm depth.

(iii) The acid peat had a pH_w of 5.5 in the surface 75 mm but no pH_w was recorded lower in the profile. An indication of a response to liming ($P < 0.10$) was recorded 3.5 years after lime treatments were applied.

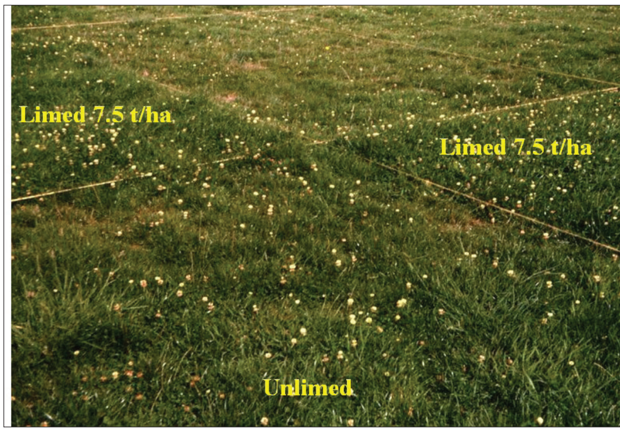

PLATE 3 — Effects of heavy rates of limestone (7.5 t/ha) on pasture grown on a Krasnozem (Ferrosol) with an initial pH_w of 5.5 when measured on 29 March 1973 at Central Castra (Rowe 1982).

(iv) The Krasnozem (Ferrosol) had an initial pH_w of 5.2 in the surface 0–75 mm and 5.0 in the 75–130 mm. Pasture yields increased linearly between limestone rates from 0.0–7.5 t/ha before decreasing at 10 t/ha when measured in the second and third autumns after application.

Aluminium toxicity

Field experiments using limestone to alleviate aluminium toxicity

Agricultural limestone was applied at rates between 0–20 t/ha on two Krasnozems (Ferrosols) with an initial pHw 5.1 and 5.4 following winter cultivation. Subsequently, its effects on spring-sown sugar beet (Anon 1981) and poppies (Temple-Smith *et al.* 1983) were measured at both sites in consecutive years. Its effects on onions (Temple-Smith & Laughlin 1985b) were measured at only one site (site with higher initial pH) in the third year:

(i) Sugar beet responded quite dramatically to increasing rates of limestone applied at rates of 0–20 t/ha on Krasnozems (Ferrosols) with pH_w 5.1 and 5.4 although satisfactory sugar yields from sugar beet (>10 t/ha) can be expected on soils with a pH_w of about 5.8. Increases in sugar yields were attributed to the correction of aluminium toxicity based on the high amount of misshapen roots and 'fanging' in plots where no limestone or low rates of limestone had been applied: these were associated with higher levels of extractable aluminium in the soil profile (Anon 1981). The effect cannot be attributed to manganese toxicity as sugar beet appears to be highly tolerant of manganese (Temple-Smith & Koen 1982).

(ii) Poppies were sown at the same two sites in the following spring. Responses to agricultural limestone applied in the previous year were measured (Temple-Smith *et al.* 1983). These experiments confirmed that poppies are extremely sensitive to soil acidity with effects being attributed primarily to the alleviation of aluminium toxicity. However, they noted that the relative effects of aluminium and calcium on yields could not be resolved because the reductions in soluble aluminium and increases in calcium have been confounded by the application of lime. However, poor tap root development and abnormal lateral root growth is consistent with the stunted root growth of poppies when grown without lime or low rates of limestone. These effects were similar to growth of poppy roots when grown, even at relatively low concentrations of aluminium, in solution culture (Temple-Smith 1982).

(iii) Onion bulb yield (y) at dry maturity (t/ha) and soil pH_w of surface 0–100 mm increased linearly at each site in proportion to the rate of limestone (L) applied ($y = 39.25 + 1.13$ L; $R^2 = 0.83$; pHw $=5.46 + 0.096$ L; $R^2 = 0.99$) (Temple-Smith & Laughlin 1985a, 1985b). They found that 95% of the total root length was restricted to the surface 200 mm of soil where $pH_w \leq 5.0$ in the 200–300 mm segment. However, more than half of the root length was below a depth of 200 mm when pH_w in the 200–300 mm segment was 6.3. Highest yields were obtained when 40–60% of total root length was present at depths below 200 mm at the start of bulb formation.

A regression of the percent of total root length below 200 mm depth against soil pHw at a depth of 200–300 mm indicated that low subsoil pH_w was restricting rooting depth.

Aluminium solution culture experiment

A preliminary aluminium solution culture experiment was conducted to assess the relative sensitivity to aluminium toxicity and probable responsiveness to liming of ten crop and forage species used in Tasmania (Temple-Smith 1982). These included sugar beet and poppies that were used in the field experiments discussed above. However, onions were not included. This group of ten included some cultivars bred in Tasmania.

Shoot dry matter was a poor indicator of relative sensitivity of species to aluminium but root yields and root extension growth were both good indicators of aluminium toxicity. Sensitive species (barley, sugar beet, Brussels sprouts, poppy and lucerne) all produced the greatest root growth in solutions containing aluminium at 0 μM but in large-seeded legumes (lupin, green bean and green pea) low levels of aluminium (25–100 μM) stimulated root growth while higher concentrations depressed it.

Species were ranked in order from the least to most tolerant to aluminium based on root growth and the occurrence of aluminium toxicity symptoms on the roots: sugar beet, Brussel sprout, poppies and lucerne were less tolerant than the barley cultivars Proctor and Shannon. These were all less tolerant than oats, green bean and green pea which were all less tolerant than lupin.

Thickening and necrosis of primary (1°) and secondary (2°) apices were recorded at 25 μM aluminium for sugar beet, Brussels sprouts, poppies and lucerne. Thickening of 2° apices but without necrosis were recorded at 50 μM aluminium for both Proctor and Shannon barley. At 200 μM aluminium, green bean showed necrosis of 1° and 2° apices, green pea showed severe distortion and cracking of 1° and 2° roots while oats showed slight necrosis of 2° nodal apices. Lupins, on the other hand, showed thickening

PLATE 4 — The susceptibility of roots of Shannon Barley to increasing levels of solution aluminium from left to right: 0, 25, 50,100, 200 and 400 μM Aluminium (Temple-Smith 1982).

and necrosis of 1° and 2° apices at 400 μM aluminium.

The report (Temple-Smith 1982) contains colour photos of roots of poppies, the barley cultivar Shannon, and lupin after two weeks of growth in a range of aluminium concentrations (0, 25, 50, 100, 200 and 400 μM Al). It also contains close-up views of aluminium toxicity on roots of poppy, sugar beet, Shannon barley, green peas and lupin.

Liming to reduce cadmium levels in potatoes and carrots

Until the early 1980s, the rock phosphates used to make phosphatic fertilisers contained relatively high levels of cadmium impurities. This, coupled with the intensive cropping history on Krasnozems (Ferrosols) and associated use of high rates of phosphate fertiliser has resulted in relatively high cadmium levels in the soil (Sparrow *et al.* 1992) with about 14% of Tasmanian soils producing potatoes exceeding the then Australian maximum permitted concentration of cadmium of 0.05 mg/kg fresh weight which equates to 0.25 mg/kg DM. Subsequently, this concentration was doubled to 0.1 mg/kg fresh weight (Sparrow pers. comm.).

Surface application of agricultural limestone to three different sites at rates of 0–30 or 0–40 t/ha did not reduce cadmium levels in potato tubers despite incorporation in the surface using a rotary hoe 4–12 weeks before planting. However, tuber cadmium levels increased as the amount of cadmium applied in phosphatic fertilisers increased (Sparrow *et al.* 1993a). Subsequently, residual effects of limestone applied (0–30 t/ha) on cadmium levels in potato tubers were measured at two of the above sites either two or three years later. This followed further mixing of limestone in the soil profile by potato harvesting machines and a further two or three years for limestone to react with soil. Tuber cadmium levels declined linearly in proportion to the rate of limestone applied by about 25% to values of about 0.1 mg/kg DM, equivalent to 40% of the permissible level.

Five years after limestone was applied at one of the above sites and following further mixing with a potato harvester, carrots were sown and cadmium content of the roots was measured. Again, cadmium content declined linearly with the rate of limestone, by about 50%, to 0.06 mg/kg DM which is equivalent to 24% of the permissible level (Sparrow & Salardini 1997).

Liming improves structure and hydraulic conductivity of a Krasnozem (Ferrosol)

A softer soil surface that was subject to more summer cracking was observed after limestone was applied at 15 t/ha to the surface of an established pasture grown on a Krasnozem (Brown Ferrosol). Furthermore, liming decreased penetration resistance and increased hydraulic conductivity. These structural improvements were associated with increased 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. Decreases in soil penetration resistance due to liming increased the likelihood of pugging from livestock but may improve the ease of tillage (Kirkham 2003, Kirkham *et al.* 2007).

Available water

Despite liming (15 t/ha) altering soil structure (Kirkham *et al.* 2007) it did not increase available soil water capacity of the soil under an unirrigated barley crop as measured by the difference between the moisture held at field capacity and wilting point. However, the rate of water extraction from higher yielding limed plots was greater than that from un-limed plots (Rowe & Johnson 1995).

In events when rainfall is sufficient to satisfy the soil water deficit on limed plots then the deficit on unlimed plots would be exceeded, and lost to deep drainage. In such an instance, limed plots would have a net gain in available water available for evapotranspiration during the growing season and, consequentially, potential for more growth.

Artemisia

Agronomic practices required to grow the medicinal crop, *Artemisia annua* L. to produce antimalarial constituents, artemisinin and artemisinic acid, were investigated to assess the potential of this crop to be grown in Tasmania. Plants grew to a height of up to 2.5 m at maturity (Laughlin *et al.* 2002) with antimalarial constituents concentrated in leaves and flowers (Laughlin 1995).

Fine-ground limestone applied at 10 t/ha to a Krasnozem (red ferrosol) increased soil pH_w from 5.0 to 5.5 and leaf dry matter yield of a Yugoslavian cultivar from 1.0 to 6.5 t/ha and a Chinese cultivar from 4.5 to 8.0 t/ha without affecting concentrations of either artemisinin or artemisinic acid in the leaves (Laughlin 1993). Subsequently, a pot experiment was conducted in a greenhouse using the same soil and strains of *A. annua* as above. Fine-ground calcium hydroxide was applied to the surface at rates equivalent to 0, 1.0, 2.5, 5.0, 10.0, 20.0 and 40.0 t/ha. The lime was then uniformly mixed through the soil to produce mean soil pH_w values of 5.0, 5.2, 5.3, 5.4, 6.0, 7.4 and 8.2. *A. annua* L. achieved maximum yield of both dry matter and antimalarial constituents at pH_w from 5.5–6.0 although some varieties have a wider tolerance of pH_w up to 8.0 (Laughlin 1993).

Liming to ameliorate plant disease

'Clubroot' or 'finger and toe' disease *(Plasmodiophora brassicae)* of cabbages, cauliflowers, broccoli and Brussels sprouts occurs throughout Tasmania. Heavy dressings of lime (5–10 t/ha) are often required on soils subject to this disease to ameliorate this problem (Wade 1949a, 1949b).

Negative effects of liming

Potato common scab *Streptomyces scabies*

Tasmanian potatoes are grown predominantly on Krasnozems (Ferrosols) where the incidence and severity of potato common scab has rapidly increased when cv. Russet Burbank became the primary processing cultivar in the state (Wilson 1996). The incidence of potato common scab has been shown to be negligible on Krasnozems (Ferrosols) with a $pH_w < 5.2$ but above this pH_w no effect was detected (Lacey & Wilson 2001).

Notwithstanding early reports that liming increased potato yields (Wilson 1949), perception amongst many potato growers is that liming increases common scab in potatoes and this remains a barrier to lime use in crop rotations in Tasmania. This is despite scab-free potatoes being grown on Krasnozems (Ferrosols) that have been limed to pH_w 6.0–6.5 and the occurrence of severe outbreaks occur at pH_w <5.5 (Sparrow & Salardini 1997). However, the occurrence of potato common scab at one site was exacerbated by limestone applied at rates up to 30 t/ha. In fact, levels of potato common scab made potatoes unsuitable for processing where rates of limestone at 20 and 30 t/ha had been applied (Sparrow & Salardini 1997). However, in this instance, this was the third potato crop in five years and potato common scab inoculum may have been substantial. It should be noted that potato processing companies require at least five years between successive commercial crops and the use of clean seed to minimise scab events.

Liming-induced boron deficiency

Boron deficiency has been recorded in pasture legumes on very acid heathland soils on the west coast of Tasmania following heavy liming (Paton & Hosking 1970). Expansion of the area of land sown to poppies in the 1990s coupled with competition for cropping land from vegetable crops necessitated a move from growing poppies on Krasnozems (Ferrosols) to lighter alluvial soils. This was associated with the occurrence of boron deficiency particularly under dry conditions (Laughlin *et al.* 1998). This problem was exacerbated by liming (Laughlin 1980).

Minor uses of lime in Tasmanian agriculture

(i) Powdered limestone, dolomite and cement together with lime-sulphur have all been used to encourage suberisation on cut potato sets, thereby protecting seed potatoes from fungal and bacterial infections while in storage prior to planting (Chapman 1977).

(ii) Lime-sulphur and Bordeaux mixture: Limil® is reacted with copper sulphate to produce Bordeaux mixture and with sulphur to produce lime-sulphur. The reaction products of each have been used as fungicides (Wade 1949a).

(iii) Introduction of earthworms *Aporrectodea caliginous* and *A. longa* into pasture soils devoid of earthworms increased pasture yields by 20–75% at Rushy Lagoon in northeast Tasmania and 20–35% at Woolnorth in far northwest Tasmania (Temple-Smith *et al.* 1993). Earthworms are not considered to be adversely affected in soils with $pH_w > 5.0$ (Garnsey 1993) although liming was advocated to increase soil pH_w to 5.8 to ensure that worms thrive and breed (Farquhar 1992).

(iv) Powdered limestone is frequently added to stock feeds as a source of calcium particularly when feed is to be consumed by laying hens (Bruce 1976).

CONCLUSIONS

This review records the many roles that agricultural lime has played in the development of Tasmanian pasture and crop production between 1940 and 2020. These results provide the foundations that underpin current and future use of liming materials with the knowledge being integrated into current farming practice.

Liming has increased yields in vegetable, medicinal, pasture and forage crops grown on Krasnozems (Ferrosols). It also improved pasture production and yields of cereal and pulse crops grown on lateritic podzols (Kurosols). Similarly, liming increased fruit and pasture yields on yellow podzolics (Kurosols). It was also vital in the establishment of nitrogen fixing pasture legumes on Podosols, Ferrosols and Kurosols. All these soils lie predominately in areas where annual rainfall exceeds 750 mm.

Mechanisms underlying the responses have been attributed to increased supply of calcium and magnesium and increases in soil pH. Increases in pH improve survival of rhizobia, nodulation and nitrogen fixation capacity of legumes, increased availability of phosphorus and molybdenum and reduced manganese, aluminium and cadmium availability as well as phosphorus leaching. Notwithstanding identification of these mechanisms as primary limiting factors on some soils, other factors may be contributing to the effects although at a lower or immeasurable level. In some instances, these factors may not even be recognised, let alone considered.

Applications of lime will continue to be applied in Tasmanian agriculture as maintenance dressings to neutralise soil acidification and maintain yield responses that produce an economic return over the long term. However, risks of over-liming cannot be discounted.

Potential areas for future research

Improved soil structure and hydraulic conductivity has been reported on a Krasnozem (Brown Ferrosol) at one site (Kirkham 2003, Kirkham *et al.* 2007). The potential for liming to improve soil structure on this and other soils, particularly where permeability restricts infiltration rates and leads to runoff or sheet erosion, could be investigated.

Most responses to heavy liming in Tasmania have been recorded in areas with an average annual rainfall (AAR) above 750–800 mm. The potential of heavy liming on soils in lower rainfall areas, particularly on yellow podzolics (Kurosols) could be beneficial since these soils were acid and responsive at higher AAR levels. Any such investigation should consider whether responses to liming are being limited by macro or micro element deficiencies occurring *in situ* or induced by liming.

Future investigations into the movement of lime in soil profiles need to recognise that movement is slow (years) and account needs to be taken of horizontal as well as spatial variability. The rate of movement down the profile does not seem to be dominated by the rate of application and is probably influenced by pH-dependent cation exchange capacity. Furthermore, it cannot be assumed that nominal depth of incorporation reflects reality. Consequently, vertical sampling segments should be relatively small (25–50 mm). Another consideration would be to use very fine lime to eliminate particle size effects on the rate of dissolution of limestone particles.

The amount of agricultural liming materials applied within each of Tasmania's three Natural Resource Management (NRM) areas was calculated to be more than 1.6 times the amount of lime required to neutralise the acidifying effects of annual applications of nitrogen fertiliser within these areas (Rowe 2023). This suggests that more than sufficient lime is being used to neutralise acidification, not only by nitrogen fertilisers, but other sources of soil acidification such as atmospheric sulphur and product removal. However, more detailed analyses at an enterprise or property level would be required to confirm that sufficient lime is being applied to account for all sources of soil acidification.

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