# Effect of lupins and pasture on soil acidification and fertility in Western Australia

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**Summary.** An 'across the fence' comparison of farmer paddocks with nearby virgin bush sites was made at 3 locations, to measure the effects of lupins and subterranean clover based pastures on the chemical properties of the soil.

Estimated rates of acidification in the 0–60 cm depth were 0.29–0.55 kmol $H^+$/ha.year for wheat–lupin paddocks and 0.16–0.21 kmol $H^+$/ha.year for pasture paddocks. A significant proportion of this acidification occurred below 20 cm, particularly in the lupin paddocks (up to 70% of the total). Severe water repellency had developed at 1 location that had produced 30 lupin crops with the occasional wheat crop. Despite these detrimental effects, lupins maintained soil mineral nitrogen and organic matter contents and electrical conductivities similar to those in pasture paddocks, even though the soils in the lupin rotations had been sown to wheat more frequently.

## Introduction

The Western Australian blue lupin (*Lupinus cosentinii* L.) has been grown as a fodder crop in rotation with cereals for over 30 years in the north of the Western Australian wheatbelt, and the introduction of narrow-leafed lupins (*L. angustifolius* L.) about 15 years ago resulted in the widespread adoption of the lupin–wheat (LW) rotation. About 1 million ha of lupins is currently grown in Australia, mostly for grain production. Rowland *et al.* (1988) observed that lupins grown on infertile, coarse-textured soils increased the soil nitrogen (N) content, acted as a 'break crop' for diseases, and improved soil structure.

Although the LW rotation has apparently been a stable and productive cropping system, some Western Australian farmers have noticed a decline in wheat yields in recent years, perhaps because of increased soil acidity and water repellency. It is estimated that in the south-west land division of Western Australia, 1.1 million ha of surface soils and 1.6 million ha of subsoils are affected by acidity [pH($CaCl_2$) <4.5]. In addition, 5.9 million ha of surface soils and 3.2 million ha of subsoils [currently pH($CaCl_2$) 4.5–5.5] are at risk of developing acidity problems in the near future (Frost 1991). The development of subsoil acidity under lupins is of particular concern given the deep rooting patterns of lupins (Hamblin and Hamblin 1985) and the difficulty of ameliorating subsoils with lime application (Conyers and Scott 1989). The cultivation of lupins at Rutherglen, Victoria, caused greater acidification in the top 20 cm of soil than a continuous wheat rotation: 3.22, 4.11, and 5.26 kmol $H^+$/ha.year for continuous wheat, LW, and continuous lupin rotations, respectively (Coventry and Slattery 1991).

The cultivation of legumes may increase soil acidity through the N and carbon (C) cycles (Helyar and Porter 1989). The main acidifying processes are the oxidation of organic N to nitrate, followed by nitrate leaching (Helyar 1976); the addition of $H^+$-saturated organic matter to soil with a pH less than the pKa of the organic acid (Ritchie and Dolling 1985); and the excretion of $H^+$ by $N_2$-fixing legumes that absorb more cations than anions. Other processes are the removal of alkaline organic matter (Israel and Jackson 1982; Jarvis and Hatch 1985; Lui *et al.* 1989) and its accumulation (Williams 1980). Lupins are best adapted to soils with low clay contents and coarse textures, and these soils are also the most susceptible to the development of water repellency (McGhie 1980). Farmers have observed patchy emergence and establishment difficulties on grey sands that have produced a large number of lupin crops.

This study compared the effects of cultivation of lupins and subterranean clover (*Trifolium subterraneum* L.) based pastures on the chemical properties of the soil.

## Materials and methods

### *Locations*

Soils from an uncleared virgin bush site and 2 cultivated paddocks, all with the same soil classification, were sampled at each of 3 locations in the

**Table 1. Details of the sampling locations, number of years since clearing, crop rotations, and soils**

L, *L. angustifolius*; W, wheat; P, subterranaean clover based pasture; BL, *L. cosentinii*; UP, unimproved pasture, mostly grass and broad-leafed weeds; (W), one wheat crop about every ten years

| Location | Rotations | No. of years[A] | Rainfall (mm) | Clay (%) | Soil classification[B] |
|---|---|---|---|---|---|
| Bodallin (31°22'S., 118°52'E.) | LW, PPW | 11, 41 | 300 | 10.9 | Gn1.21 |
| Three Springs (29°32'S., 115°45'E.) | LW, P(W) | 20 | 370 | 4.4 | Uc5.22 |
| Mingenew (29°11'S., 115°26'E.) | BL(W), UP(W) | 25 | 420 | 2.4 | Uc5.11 |

[A] All paddocks had been under the rotations since clearing except LW at Bodallin.
[B] Northcote (1974).

Western Australian wheatbelt in May 1990, soon after the first autumn rains (Table 1). The sampled area of the paddocks and bush was predominantly flat at all locations, and a number of cores were examined to ensure uniformity of the soil type across each area. These samples were not collected for chemical analysis.

At each location, 1 paddock represented continuous cropping production, and the other, largely a pasture history (Table 1). Apart from soil cultivation in the cropping paddocks, the pasture and cropping paddocks within each location were managed similarly. According to the farmers, the paddocks had received equivalent types and amounts of fertiliser. No lime or N fertiliser had been applied at any site. The amounts of phosphorus (P) applied were unknown, as the farmers had not kept accurate long-term fertiliser records. Likewise, no accurate long-term yields were available.

*Soil sampling*

At Bodallin and Mingenew, adjacent cultivated paddocks were sampled about 40 m from the adjoining fence, in 3 replicates spaced 15 m apart running in a line parallel to the fence. At Three Springs, soil samples were taken in a similar pattern, but the paddocks were about 500 m apart. Each replicate consisted of 3 soil profile cores collected within a 1-m radius and bulked. The soils were collected by hand using a 75-mm core, at depth intervals of 0–5, 5–10, 10–20, 20–40, and 60–80 cm (at Bodallin samples were not collected below 60 cm). The soil in both paddocks at Bodallin and the LW paddock at Three Springs had been cultivated before sampling.

A similar sampling procedure was used in uncleared native bush sites (referred to as paddocks) within 100 m of the cultivated paddocks. At Mingenew the sandy soil in the bush paddock was drier than in the cultivated paddocks and samples could not be collected below 60 cm.

*Chemical analyses*

Samples were air-dried and sieved, and the >2 mm fraction was discarded. The following analyses were performed: bicarbonate-extractable K (Colwell 1963); mineral N ($NO_3^-$ using a specific ion electrode in 1 : 5 soil : water extract, plus exchangeable $NH_4^+$ in 1 : 5 soil : 1 mol KCl/L extract); organic C (Walkley and Black 1934); electrical conductivity (EC) in 1 : 5 soil : water extract; pH and total extractable aluminium (Al) in a 1 : 5 soil : 5 mmol KCl/L extract (Carr *et al.* 1991); buffering capacity in 1 : 5 soil : 5 mmol KCl/L extract (Ritchie and Dolling 1985); water repellency by the molarity ethanol drop (MED) test (King 1981). Mean acidification rates were estimated by the method of Ridley *et al.* (1990).

*Statistical analyses*

Results of each chemical analysis were compared by analysis of variance using each paddock as the main plot, with each depth as a subplot. The relationship between pH and Al was examined using linear and logarithmic equations.

## Results

*Soil pH*

At all 3 sites, pH values in some part, if not all, of the soil profile of the cultivated paddocks were lower ($P<0.05$) than in the bush paddocks (Fig. 1). The pH of the top 20 cm of soil in the cultivated paddocks at Bodallin, was about 0.4 units lower than in the bush paddock. At 20–40 cm depth in the LW paddock, the pH was about 0.3 units lower than in the other paddocks. The pH of the 3 paddocks at Bodallin was similar at 40–60 cm depth.

In the top 5 cm of soil at Three Springs, the pH of the LW paddock was about 0.5 units lower than that of the bush paddock, while the pH of the P(W) paddock was 0.2 units higher. At 5–60 cm depth, the pH of the cultivated paddocks was 0.2–0.5 units lower than that of the bush paddock. Below 60 cm depth, soil pH values of the 3 paddocks were similar.

Throughout the profile at Mingenew, the pH of the soil in the BL(W) paddock was 0.3–0.7 units lower than that of the bush paddock; the greatest difference occurred below 60 cm, where the pH of the BL(W) paddock was 1.3 units lower than the UP(W) paddock. The pH profile of the UP(W) did not differ ($P$>0.05) from that of the bush paddock in the top 10 cm but was about 0.2 units lower below 10 cm.

*pH buffering capacity*

The pH buffering capacity of the virgin soil at Bodallin decreased with depth in the top 20 cm, from 0.58 to 0.48 cmol $H^+$/kg.pH unit, and then increased to 0.91 cmol $H^+$/kg.pH unit at 40–60 cm (Fig. 2). At the other 2 locations, the buffering capacity of the virgin soils decreased with depth from 0.35 and 0.71 cmol $H^+$/kg.pH unit in the top 5 cm at Three Springs and Mingenew, respectively, to about 0.25 cmol $H^+$/kg.pH unit below 10 cm at both sites.

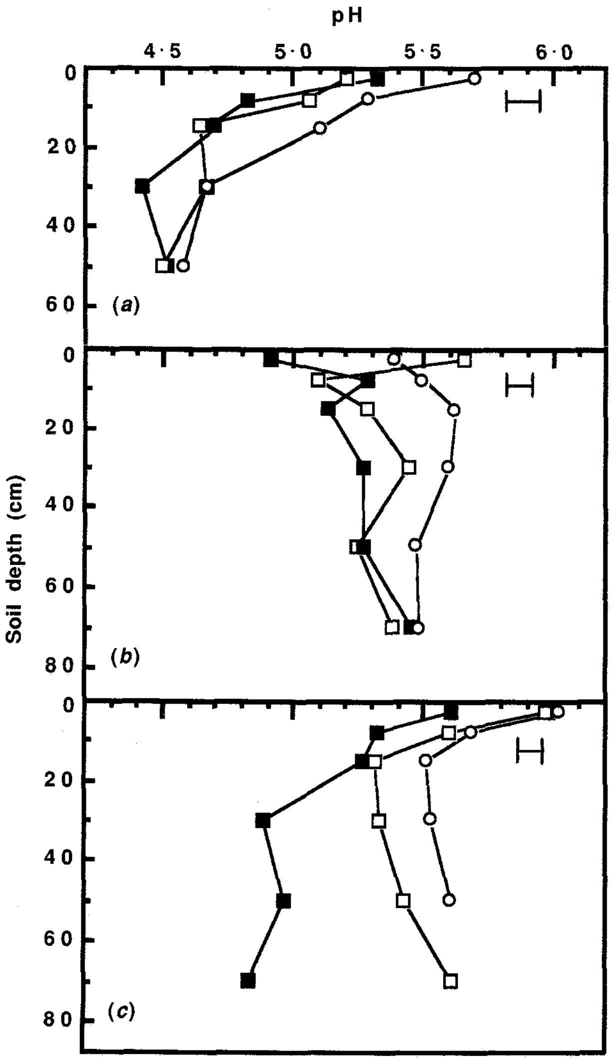


**Fig. 1.** Soil pH profiles (0.005 mol KCl/L extract) at (*a*) Bodallin (○ bush; □ PPW; ■LW); (*b*) Three Springs [○ bush, □P(W), ■LW]; and (*c*) Mingenew [○ bush, □UP(W), ■BL(W)]. Horizontal bars indicate l.s.d. at $P$ = 0.05.

In the top 5 cm of soil at Bodallin and Three Springs, the pH buffering capacity of the cultivated paddocks was greater ($P$<0.05) by about 0.1 cmol $H^+$/kg.pH unit than in the bush paddock. In top 5 cm of soil at Mingenew, the pH buffering capacity of the cultivated paddocks was less ($P$<0.05) by about 0.15 cmol $H^+$/kg.pH unit than the bush site. These differences between paddocks largely reflect the differences in soil organic C content. Below 5 cm at all 3 sites, the pH buffering capacities were similar between paddocks.

*Acidification*

In the PPW and LW paddocks at Bodallin, acidification relative to the bush paddock occurred in the top 60 cm of soil at rates (± s.e.) 0.17 ± 0.03 and 0.29 ± 0.07 kmol $H^+$/ha.year, respectively (Fig. 3). The rotations caused similar rates of acidification in the top 20 cm of soil; however, in the 20–40 cm layer, the acidification rate in the LW paddock was 0.12 ± 0.03 kmol $H^+$/ha.year, while no acidification ($P$>0.05) occurred in this soil layer in the PPW paddock.

The estimated acidification rates throughout the whole soil profile at Three Springs were similar to those at Bodallin, but significant ($P$<0.05) acidification also occurred at the 20–40 cm depth at Three Springs. Acidification occurred to 60 cm depth under both rotations, with the highest rate (0.11 ± 0.03 kmol $H^+$/ha.year) occurring in the 20–40 cm layer of soil in the LW paddock. Alkalinisation occurred in the top 5 cm of the pasture paddock.

The highest rate of acidification was measured in the BL(W) paddock at Mingenew (a total of 0.55 ± 0.09 kmol $H^+$/ha.year throughout the sampled profile), and this value was an underestimate because, unlike at the other

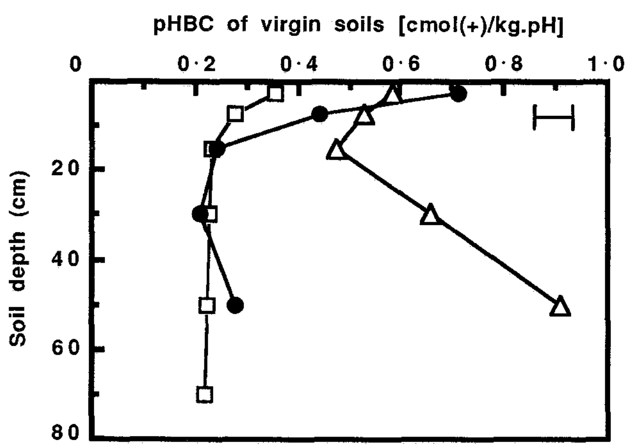


**Fig. 2.** Profiles of pH buffering capacities of virgin soils at Bodallin (△), Three Springs (□), and Mingenew (●). Horizontal bars indicate l.s.d. at $P$ = 0.05.

locations, the cultivated paddocks were not sampled to a depth where the pH was similar to that of the bush paddock. Acidification was greatest (0.21 ± 0.05 kmol $H^+$/ha.year) in the deepest samples (40–60 cm). No acidification ($P$>0.05) occurred in the top 20 cm of the UP(W) paddock, whereas below 20 cm, the UP(W) rotation caused less than one-third of the acidification of BL(W).

*Total extractable aluminium*

Aluminium concentrations in the soil extracts were <13 μmol/L at all sites and depths (Fig. 4). Aluminium concentration was linearly related ($r^2$ = 0.68) to pH at Bodallin, with greater Al at lower pH; however, extractable Al was poorly correlated ($r^2$ = 0.30) with pH at Mingenew and Three Springs. The variation accounted for was not greater with logarithmic equations.

The concentrations of extractable Al in the top 10 cm of soil in the cultivated paddocks at Bodallin were greater by 3–5 μmol/L than in the bush paddock. In the 20–40 cm layer, the Al concentration was greater by 7 μmol/L in the LW paddock than in the bush and PPW paddocks, which did not differ.

There were no differences ($P$>0.05) between the Al concentration profiles of the 3 paddocks at Three Springs. At 10–60 cm depth at Mingenew, the Al concentrations were greater in the BL(W) than the UP(W) paddock.

*Mineral nitrogen*

In the top 5 cm of soil at Bodallin, the PPW paddock had about 10 μg/g more mineral N than the bush paddock. To 20 cm depth, the LW paddock had more mineral N by about 5 μg/g than the bush paddock, (Fig. 4). No other significant differences were observed.

At Three Springs, the bush paddock had a relatively low and constant mineral N content of about 5 μg/g throughout its soil profile. In the top 10 cm of soil, the P(W) paddock had a greater ($P$<0.05) N content than the bush paddock, particularly in the top 5 cm where the difference was 20 μg/g. The LW paddock had an N content 5–12 μg/g greater than the bush paddock to a depth of 40 cm.

The only difference ($P$<0.05) at Mingenew was in the top 5 cm of soil where the mineral N contents of the BL(W) and UP(W) paddocks were about 10 μg/g greater than the bush paddock.

*Bicarbonate-extractable potassium*

At Bodallin, the cultivated paddocks had 30–50 μg/g less bicarbonate-extractable K in the top 20 cm of soil than the bush site (Fig. 4). The K contents of the cultivated paddocks did not differ ($P$>0.05) from each other except in the top 5 cm of soil, where the LW paddock had 30 μg/g more K than the PPW paddock.

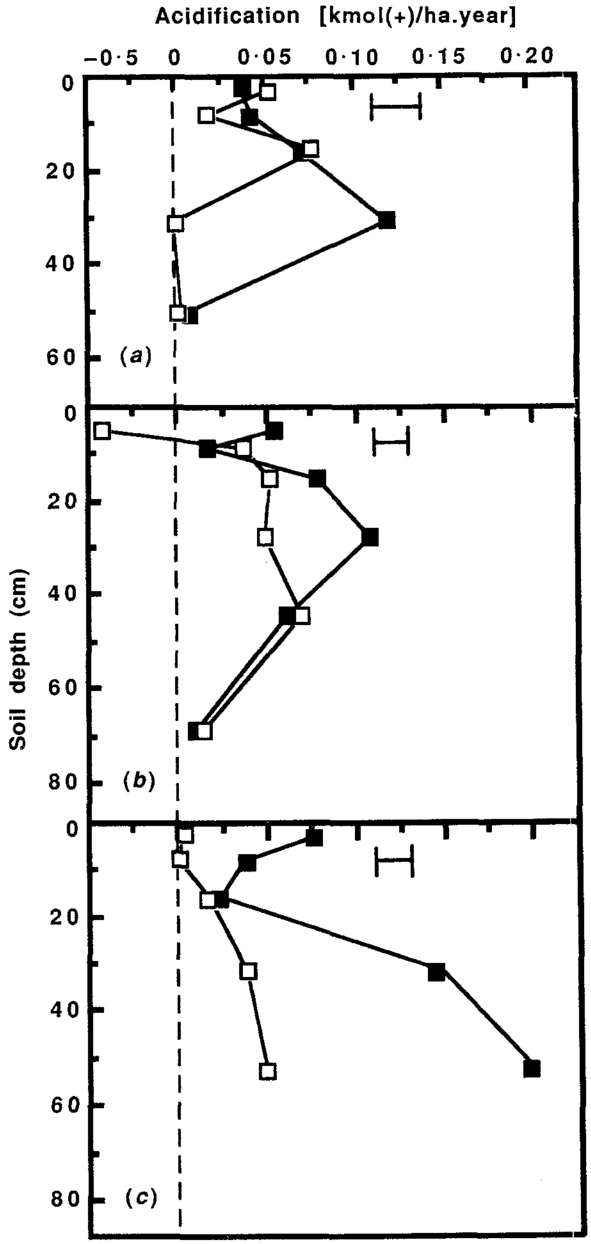


**Fig. 3.** Acidification rates for soil profiles at (*a*) Bodallin (□ PPW, ■ LW); (*b*) Three Springs [□ P(W), ■ LW]; and (*c*) Mingenew [□ UP(W),■ BL(W)]. Total acidification rates (kmol/ha.year) throughout the sampled profile were (*a*) 0.17 for PPW and 0.29 for LW; (*b*) 0.21 for P(W) and 0.37 for LW; and (*c*) 0.16 for UP(W) and 0.55 for BL(W). Horizontal bars indicate l.s.d. at $P$ = 0.05.

At Three Springs, the K content of the bush paddock was <25 μg/g, considerably less than in the bush paddock at the other 2 locations. The cultivated paddocks had received K fertiliser; consequently, the LW paddock had about 15 μg/g more K in the top 10 cm than

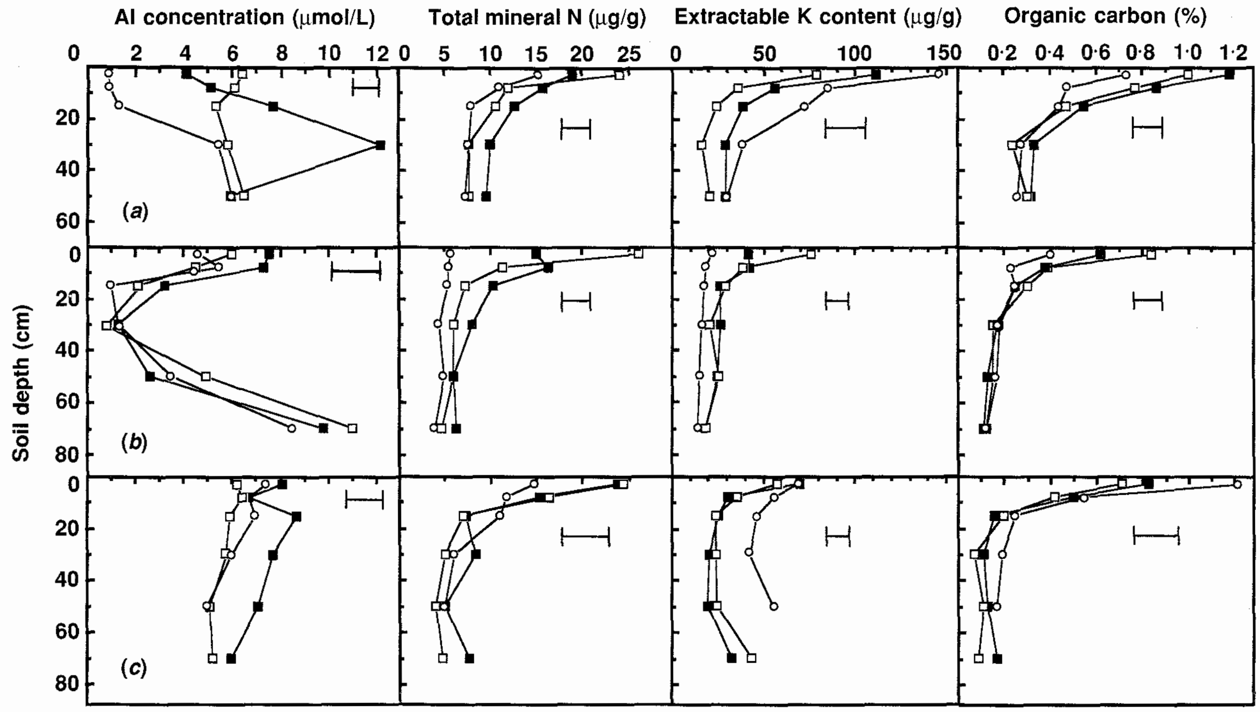


**Fig. 4.** Total extractable aluminium (0.005 mol KCl/L extract), total mineral nitrogen, bicarbonate-extractable potassium, and organic carbon content in the soil profiles at (*a*) Bodallin (○ bush, □PPW, ■LW); (*b*) Three Springs [○ bush, □P(W), ■ LW]; and (*c*) Mingenew [○ bush, □ UP(W), ■ BL(W)]. Horizontal bars indicate l.s.d. at $P = 0.05$.

the bush paddock, while the P(W) paddock had 35 μg/g more K in the top 5 cm of soil than the LW paddock.

At Mingenew, there was no difference ($P$>0.05) between the 3 paddocks for K content in the top 5 cm of soil. Below 5 cm, the cultivated paddocks had about 30 μg/g less K than the bush site.

*Organic carbon*

In the top 5 cm of soil at Bodallin, the organic C content was about 0.3% greater in the PPW paddock than in the bush paddock, and about 0.2% greater in the LW paddock than the PPW paddock (Fig. 4). Both cultivated paddocks had about 0.3% more organic C in the 5–10 cm soil layer than the bush paddock; below 10 cm, there was no difference ($P$>0.05) in the organic C contents of soils of the 3 paddocks.

In the top 5 cm of soil at Three Springs, the LW had 0.2% more organic C than the bush paddock, and the P(W) 0.2% more organic C than the LW paddock. Below 5 cm, organic C contents of the 3 paddocks did not differ ($P$>0.05).

At Mingenew, the organic C contents of the 3 paddocks did not differ ($P$>0.05), except in the top 5 cm of soil where the bush paddock had about 0.3% more organic C than the cultivated paddocks.

*Electrical conductivity*

At Bodallin, the EC of the PPW paddock differed ($P$<0.05) from that of the bush paddock only in the top 5 cm, where it was 0.02 dS/m greater (Fig. 5). The EC of the LW paddock was 0.02 dS/m greater than the bush paddock in the 5–10 cm layer of soil only.

Both of the cultivated paddocks at Three Springs had greater EC to 40 cm depth than the bush paddock. The cultivated paddocks did not differ ($P$>0.05), except in the top 5 cm where the EC of the P(W) was 0.02 dS/m greater than the LW paddock.

At Mingenew, the BL(W) paddock had an EC 0.02 dS/m greater than the other paddocks in the top 5 cm of soil. No other significant differences were observed.

*Water repellency*

No water repellency was evident on the soil at Bodallin or the bush sites at the other locations (Table 2). At Three Springs, the P(W) paddock had a MED test score of 2.7–3.6 in the top 10 cm of soil, while the LW paddock had a lower ($P$<0.05) MED score of 1.0 in the top 5 cm. At Mingenew, the BL(W) paddock had greater ($P$<0.05) MED scores than the UP(W) in the topsoil, particularly in the top 5 cm of soil where the score was 4.0 for the BL(W) paddock.

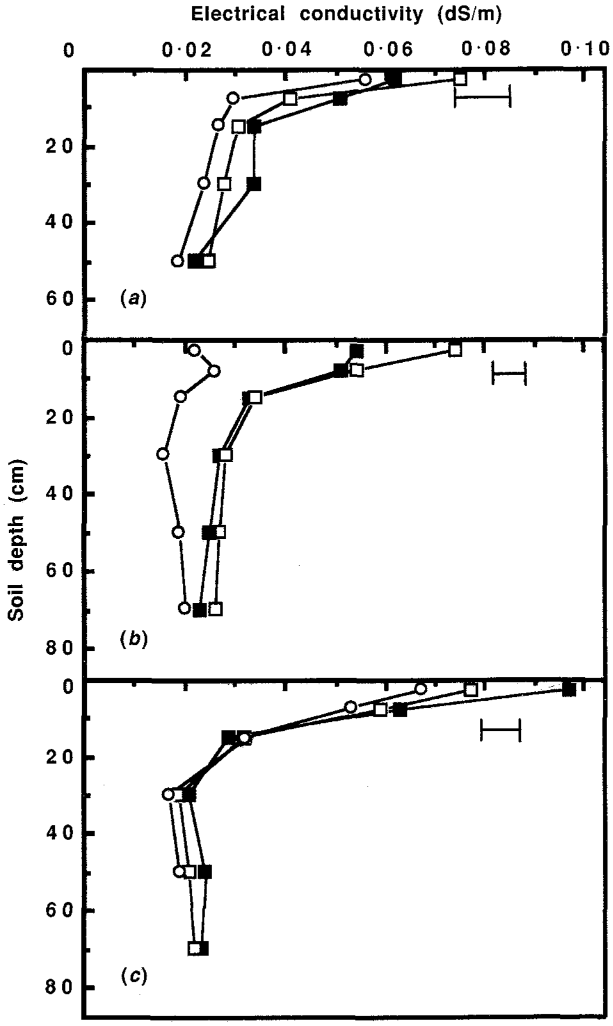


**Fig. 5.** Electrical conductivity in the soil profiles at (*a*) Bodallin (○ bush, □ PPW, ■ LW); (*b*) Three Springs [○ bush, □ P(W), ■ LW]; and (*c*) Mingenew [○ bush, □ UP(W), ■ BL(W)]. Horizontal bars indicate l.s.d. at $P = 0.05$.

## Discussion

Soil acidification had occurred under the rotations at all 3 sites, although none had a history of declining productivity. The pH values of the cultivated paddocks are not low enough to decrease productivity; similarly, extractable Al concentrations are not high enough to decrease wheat growth (Carr *et al.* 1991). However, the sites were much less buffered against pH changes than sites reported in eastern Australia (Helyar *et al.* 1990; Ridley *et al.* 1990; Coventry and Slattery 1991), and the potential for pH decline and the development of acidity problems is great.

The fastest rate of pH decline was about 0.04 units/year in the top 20 cm, which was less than those reported for subterranean clover pastures in Western Australia (Barrow 1964) and New South Wales (Williams 1980), and less than half of that reported for LW rotation in Victoria (Coventry and Slattery 1991). Given the moderate pH decline and low pH buffering capacities of the soils in the present study, the rates of acidification were much less than those reported in eastern Australia. In this study, the acidification rate in the 0–20 cm layer of soil under rotations including lupins was about 0.16 kmol $H^+$/ha.year, and this would require about 8 kg/ha.year of lime to neutralise. Coventry and Slattery (1991) reported rates as high as 5.26 kmol $H^+$/ha.year (equivalent to 263 kg/ha.year of lime) at the same depth. Relatively low rates of acidification were measured elsewhere in Western Australia (Dolling 1991) and in Victoria (Ridley *et al.* 1990); however, even those rates were greater than our estimates. Differences in acidification rates may be partly attributed to the different methods used to measure pH buffering capacity.

Many factors could be causing low rates of acid addition. Data of Williams (1980) and Ridley *et al.* (1990) suggest that the rate of acidification is low when soil pH is low (i.e. 4.0–4.5); however, soils in our study had pH values >4.5. The average rainfall and soil fertility at our sites are considerably lower than in eastern Australia, resulting in less productivity. Coventry and Slattery (1991) recorded wheat yields in LW rotation that were up to 5 times those expected in Western Australia; hence, small amounts of product removal would result in low rates of soil acidification in Western Australia. Also, Western Australia experiences a mediterranean climate with very little rain in summer. Together with inherently low N contents, the potential for nitrification over summer and nitrate leaching may be smaller in Western Australia than in the eastern States.

**Table 2. Water repellency scores (MED test; King 1981) in the soil profiles at Three Springs and Mingenew**

Score range was 0–5, where scores >2 are considered severe enough to cause establishment difficulties (Oades 1988)
All scores at Bodallin were zero
L, *L. angustifolius*; W, wheat; P, subterranean clover based pasture; BL, *L. cosentinii*; UP, unimproved pasture, mostly grass and broad-leafed weeds; (W), one wheat crop about every ten years

| Location and rotation | Soil depth 0–5 cm | 5–10 cm | 10–20 cm |
|---|---|---|---|
| Three Springs | | | |
| P(W) | 2.7 | 3.6 | 0 |
| LW | 1.0 | 0.0 | 0 |
| Mingenew | | | |
| BL(W) | 4.0 | 1.1 | 0 |
| UP(W) | 1.1 | 0.0 | 0 |

The effects of product removal and the relative importance of the C and N cycles could not be assessed from this study because farmer records were inadequate.

Lupins and pasture caused similar rates of acidification in the 5–20 cm layer of soil. Below 20 cm, appreciable acidification occurred under lupins (up to 70% of that estimated throughout the whole profile). In the BL(W) paddock at Mingenew, the measured acidification rate at 40–60 cm depth was 0.21 kmol $H^+$/ha.year. If lime could be placed at this depth, at least 10 kg/ha.year would be required to neutralise this acidity. Significant acidification was also measured by Coventry and Slattery (1991) in the subsoil under lupins. Considering that soil at Mingenew was not sampled to greater depth, the total acidification measured is probably an underestimate.

Causes of subsoil acidification are poorly understood. Hamblin and Hamblin (1985) measured the rooting characteristics of several plants grown on a deep sandy soil, and for lupins 60% of the total root length occurred below the top 20 cm of soil, whereas the corresponding proportion for pasture legumes was <30%. Proton excretion by plant roots occurs in zones of high cation uptake (Loss *et al.* 1993); hence, when lupins take up moisture and nutrients from the subsoil, particularly with the onset of spring, subsoil acidification may occur. In general, soils in Western Australia have light textures and low organic matter contents, and because a large proportion of the rainfall occurs in winter, $H^+$ may leach from top soils to subsoils.

The LW rotation at Bodallin maintained a higher K concentration in the top 5 cm of soil than the P(W) paddock, which supports the hypothesis that lupins absorb $K^+$ from heavier textured subsoils and then deposit the K in the topsoil through organic matter cycling (Rowland *et al.* 1988). Heavy-textured soils are better buffered against pH changes than light-textured soils, and only a small rate of pH decrease can be expected in heavy subsoils under lupins; however, high rates of lime will be required to increase the pH when the soil eventually requires amelioration. In the deep, coarse sands on which most lupin crops are grown in Western Australia, $NH_4^+$, $K^+$, and other cations tend to be concentrated near the organic layer of the surface soil, and greater acidification would be expected in the upper horizons; however, this was not the case at Mingenew.

In the top 5 cm of soil in the pasture paddocks, alkalinisation occurred at Three Springs and no acidification at Mingenew. This was likely to be caused by deposition of alkaline organic anions on the soil surface and their subsequent oxidation under the pastures. In contrast, high rates of acidification were measured in the top 5 cm of soil in the PPW paddock at Bodallin, probably a result of the mixing of the alkaline surface soil with deeper acid soil layers during soil cultivation several days before sampling and during the cropping phases of the rotation.

Lupin cultivation was associated with an increase in water repellency in sandy soils, and this may pose a long-term limitation on soil fertility. In the BL(W) paddock at Mingenew, which had produced the most lupin crops of the 3 sites, water repellency had developed that was severe enough to cause crop establishment problems. Water repellency was also evident in the LW paddock at Three Springs, but to a lesser extent. Water repellency did not develop at Bodallin, probably because of the relatively high clay content.

Despite the detrimental effects of lupins on soil fertility in this study, several benefits were also observed. The inclusion of lupins in rotations maintained the N contents of the topsoil at levels similar to those for the pasture, even though the lupin paddocks at Bodallin and Three Springs were sown to wheat more frequently than in the pasture paddocks. Organic matter contents and electrical conductivities of the topsoils of the lupin paddocks were also maintained at levels similar to the pasture paddocks at Bodallin and Three Springs.

The implications of this study are limited by the methods. Only 3 sites were sampled on a small range of soil types, and extrapolation of the results to other parts of the wheatbelt should therefore be viewed with some caution. While no obvious gradients in soil type were evident across paddocks, small chemical variations may have existed and the acidification rates measured should be viewed as estimates, especially at Mingenew, where the greatest acidification occurred in the deepest soil sampled.

In conclusion, this study indicates that the LW rotation is not a stable production system in the long term, and the problems of acidification and water repellency must be addressed. Although acidification rates are much less than those reported in the eastern States, a larger proportion of the acidification occurred at depth in Western Australia. Methods are required to minimise and to ameliorate subsoil acidification and water repellency.

**Acknowledgments**

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