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Changes in Nitrogen and Organic Carbon of Wheat-growing Soils after Various Periods of Grazed Lucerne, Extended Fallowing and Continuous Wheat

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Abstract

Changes in total and mineral nitrogen and organic carbon were measured over a nine year period in two contrasting soils of northern New South Wales after various durations of grazed lucerne, extended fallowing and continuous wheat growing.

At least 2½ years of lucerne ley were required to raise the total soil nitrogen above the original level on both soil types. For each year of lucerne growth the average increase (above the control treatments) in total soil nitrogen (0-15 cm) was equivalent to about 140 kg nitrogen ha^{-1} in the black earth and about 110 kg nitrogen ha^{-1} in the red-brown earth. Significantly higher levels of soil nitrogen were maintained after the lucerne treatments throughout the 9 years of measurement on the black earth and for 5 years on the red-brown earth. Lucerne had a much larger effect on nitrogen than on organic carbon, which was significantly increased only in the black earth.

There were very large increases in mineral nitrogen (0-15 cm) in the first year of measurement after lucerne. Levels remained greater than they were originally for the first 4 years, and they were greater for 7 years in the black earth and 4 years in the red-brown earth following lucerne than following continuous wheat or extended fallow. The decline in mineral nitrogen during wheat cropping after lucerne was greatly increased by excessive rainfall (574 mm or more) during the fallow. Leaching was greater in the red-brown earth than in the black earth, and this explained occasional differences in nitrogen uptake by wheat between the two soil types. Some evidence suggested that under moderately moist conditions nitrogen mineralization from lucerne-fixed nitrogen was greater in the red-brown earth than in the black earth but under drier conditions it was less.

Introduction

While considerable effort has been made to document the beneficial effects of subterranean clover and other annual pasture legumes on the fertility of wheat-growing soils in Australia (Donald and Williams 1954; Watson 1963, 1969), there are virtually no published data on the corresponding effects of lucerne, even though it is the only pasture legume commonly grown in the northern wheat-belt. Minimal data were recorded by Wells (1970) for five sites in the Victorian mallee, showing that 2 years of grazed lucerne had little if any effect on total soil nitrogen, but a large effect on soil nitrate in the upper 15 cm of soil. Overseas research, particularly in Canada, also shows that lucerne invariably increases mineral nitrogen in soils after the lucerne leys. However, the effect on total soil nitrogen seems to depend on the initial nitrogen level of the soil. Where this was high (0·20% or more), nitrogen levels did not increase and sometimes decreased during a lucerne ley (Dubetz and Hill 1964; Ferguson and Gorby 1971), but where it was lower (<0·16%) there was a small increase in total nitrogen and soil organic matter (Hoyt and Hennig 1971).

A survey of the nutrient status of soils of the northern wheat-belt of New South Wales showed that all red-brown earths and the majority of black earths contained less than 0·16% total nitrogen; most of the former soils actually contained less than 0·10% total nitrogen (Hallsworth *et al.* 1954). A detailed study on a representative of each of the above soils has already demonstrated the beneficial effects of grazed lucerne on the long-term yields and nitrogen uptake of subsequent wheat (Holford 1980). This present paper provides results from the same two experiments showing changes in soil organic carbon and total and mineral nitrogen after various periods of grazed lucerne and extended fallowing. It also describes changes in mineral nitrogen levels during seasonal fallow periods and at various depths in the soil profiles.

Materials and Methods

The two experiments were on adjoining sites, 10 km south-east of Tamworth in the northern wheat-belt of New South Wales. Both sites had long histories of cereal growing, and for the five years (1961–65) prior to the experiment the red-brown earth was used for oats, wheat, fallow, grain sorghum, and fallow, while the black earth was used for wheat, fallow, grain sorghum, wheat, and fallow.

Experimental Treatments

Detailed information on the experimental design and treatments were given previously by Holford and Doyle (1978). In summary, each experiment consisted of two phases, a preliminary lucerne and control treatment phase and a subsequent wheat-growing phase. The five treatments of the preliminary phase ended simultaneously in February 1970 on the black earth and January 1972 on the red-brown earth, so that their effects on soil fertility could be monitored in a continuous wheat-short fallow rotation under identical climatic conditions. The treatments were:

(1) Long lucerne ley: 5½ years on the red-brown earth and 3½ years on the black earth.
(2) Intermediate lucerne ley: 3½ years and 2½ years respectively.
(3) Short lucerne ley: 1½ years on both soils.
(4) Extended fallow (control).
(5) Continuous wheat (control).

In addition to the 1965 fallow soils were fallowed during the years preceding establishment of the short and intermediate lucerne leys. During fallow periods soils were maintained in a more or less weed-free condition by normal cultivation practices. Wheat stubble was burnt within 1 month of harvest prior to fallow cultivation in the summer and autumn of each year.

Soils

One site was on a black earth which is a calcareous black to dark greyish brown self-mulching clay (Ug 5·15) with pH 8·4, total nitrogen 0·116%, mineral nitrogen 18·1 μg/g soil, and organic carbon 1·14%. The other site was on a truncated red-brown earth which is a brown to reddish brown earthy clay (Uf 6·21) with pH 6·9, total nitrogen 0·114%, mineral nitrogen 16·5 μg/g soil, and organic carbon 1·33%. These analyses are for composite soil samples taken at the beginning of the experimental treatment (June 1966) and are representative of each experimental site to a depth of 15 cm. Mechanical analysis of a single profile sample showed the red-brown earth (0–20 cm) to contain 11·0% coarse sand, 25·5% fine sand, 19·2% silt, and 44·3% clay.

Soil Sampling and Analysis

Soil samples for chemical analysis were taken from each half-plot which received no nitrogen fertilizer. Each sample was a composite of 30 cores to a depth of 15 cm. Annual sampling was carried out at the time of wheat sowing in June, July, or August from 1970 to 1978 inclusive. To monitor seasonal changes in soil mineral nitrogen several additional samplings were carried out between wheat harvests in 1974 and 1975. Changes in mineral nitrogen to a depth of 100 cm were monitored in the continuous wheat and long lucerne treatments during the fallow periods of 1975, 1976, and 1977. Composite soil samples, consisting of two 5 cm diameter cores from each half plot, were taken at 0–15, 15–30, 30–50, 50–75, and 75–100 cm depths.

Soils samples were stored at 3–5°C prior to analysis for mineral nitrogen. Nitrate and ammonium nitrogen were extracted from field moist samples (<2 mm) using 1 M potassium chloride at 5:1 extractant:soil ratio, and then analysed by an autoanalyser procedure similar to that of Henzell *et al.* (1968). Other analyses were done on air-dried (35–40°C) samples ground to 0·5 mm. Total soil nitrogen was analysed by micro-Kjeldahl digestion in concentrated sulfuric acid using potassium sulfate, copper sulfate and selenium as catalyst, followed by autoanalysis involving colour development (625 nm) with buffered alkaline phenate. Organic carbon was determined by the Walkley–Black procedure.

Results and Discussion

Several unusual weather phenomena occurred during the 9 year period of the study, and these had large effects on the results in addition to the treatment effects. In 1972, very low rainfall during the fallow (128 mm from February to August) prevented wheat sowing on the red-brown earth and necessitated ploughing in of the crop in October on the black earth. Consequently the former soil had an unplanned 18 month fallow prior to the first wheat crop in 1973. In 1974 a hail storm damaged the wheat crops in November, causing some lodging and grain fall. Extremely high rainfall for three months (534 mm) following harvest in 1975 prevented normal fallow cultivation in early 1976, with resultant heavy growth of weeds and volunteer wheat on the black earth but not on the red-brown earth; less growth on the latter soil was apparently caused by leaching of nitrogen (Holford 1980). Fallow rainfall for each of the 9 years is given in Fig. 1. For comparison the average rainfall for the December–May period during 1960–1979 was 385 mm, while the average annual rainfall for the same period was 683 mm.

Soil Organic Carbon

Differences in carbon between the lucerne and the cultivation treatments (i.e. extended fallow or continuous wheat) were greater on the red-brown earth, but because of the large variation in this soil they were not significant, whereas on the black earth they were significant ($P < 0 \cdot 05$) in most years. Extended fallowing caused the largest decrease in organic carbon, and because the short and intermediate lucerne leys were preceded by long periods of fallow, these treatments did not maintain organic carbon levels on the red-brown earth (Table 1). The preceding fallows were shorter on the black earth, and consequently both the intermediate and long lucerne treatments increased organic carbon on this soil, whereas only the long lucerne ley increased it on the red-brown earth in the last year of the ley (1971). Generally the carbon level was proportional to the length of the lucerne leys on both soils, but in the short lucerne leys it was not significantly different from that of the non-lucerne treatments.

The marked decline in organic carbon after ploughing in the lucerne on the red-brown earth was apparently caused by the 18 months of cultivated fallow, whereas a short-lived wheat crop was sufficient to maintain organic carbon levels during the

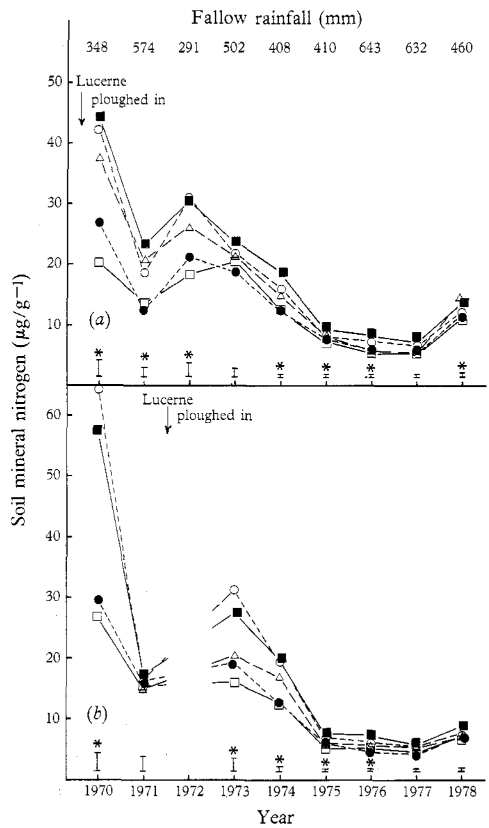

Fig. 1. Soil mineral nitrogen (0-15 cm) after various periods of lucerne ley, extended fallow, and continuous wheat cropping. Fallow rainfall indicated for each year. (*a*) Black earth. (*b*) Red-brown earth. ■——■ Long lucerne. ○– – –○ Intermediate lucerne. △ – – △ Short lucerne. •--------• Extended fallow. □——□ Continuous wheat. Vertical bars, standard errors. * Treatment effect significant ($P < 0 \cdot 05$).

Table 1. Soil organic carbon (0-15 cm) after various periods of lucerne ley, extended fallow and continuous wheat

Soil	Preceding treatment	Soil organic carbon (%) 1970	1971	1972	1973	1974	1976	1978
Black earth	Lucerne, 1966-69	1·21[A]	1·21[A]	1·18[A]	1·16	1·17	1·24	1·17[A]
	Lucerne, 1967-69	1·23[A]	1·17[A]	1·17[A]	1·20	1·16	1·19	1·13
	Lucerne, 1968-69	1·07	1·13	1·12	1·15	1·11	1·16	1·06
	Fallow, 1966-69	1·05	1·10	1·10	1·14	1·13	1·16	1·10
	Wheat, 1966-69	1·11	1·11	1·08	1·15	1·13	1·15	1·11
	Standard error	0·025	0·019	0·022	0·025	0·019	0·020	0·019
Red-brown earth	Lucerne, 1966-71	1·33	1·43	–	1·25	1·29	1·27	1·14
	Lucerne, 1968-71	1·21	1·28	–	1·15	1·20	1·21	1·06
	Lucerne, 1970-71	1·20	1·25	–	1·10	1·12	1·13	1·07
	Fallow, 1966-71	1·19	1·20	–	1·05	1·06	1·06	1·06
	Wheat, 1966-71	1·26	1·20	–	1·08	1·13	1·13	1·02
	Standard error	0·044	0·063	–	0·051	0·052	0·049	0·047

[A] Lucerne treatments > control treatments ($P < 0 \cdot 05$).

same period on the black earth (Table 1). Carbon levels tended to decrease after 1974 on the red-brown earth, whereas the increase on the black earth in 1976 was apparently associated with ploughing in of a very heavy growth of weeds and volunteer wheat which occurred during the very wet early fallow of that year. Except for a small decline after the long and intermediate lucerne treatments, carbon levels were maintained on the black earth during the period of measurement.

Total Soil Nitrogen

Total soil nitrogen increased as a result of the intermediate and long lucerne leys on both soils, remained constant in the short lucerne ley on the black earth, and tended to decrease in the other treatments during the period of the lucerne leys (Table 2). Total soil nitrogen was greatest in the long lucerne ley throughout the experiments, but often was not significantly greater ($P<0\cdot05$) than levels in the intermediate lucerne leys. Nitrogen in the short lucerne ley, which again was adversely affected by the long period of preceding fallow, was significantly greater than the cultivation treatments only in 1970 on the black earth.

Table 2. Total soil nitrogen (0–15 cm) after various periods of lucerne ley, extended fallow and continuous wheat

Soil	Preceding treatment	Total soil nitrogen (%) 1970	1971	1972	1973	1974	1976	1978
Black earth	Lucerne, 1966–69	0·136[A]	0·124[A]	0·124[A]	0·122[A]	0·121[A]	0·120[A]	0·120[A]
	Lucerne, 1967–69	0·126[A]	0·121[A]	0·122[A]	0·116[A]	0·118[A]	0·113[A]	0·113[A]
	Lucerne, 1968–69	0·117[A]	0·113	0·112	0·113	0·109	0·109	0·110
	Fallow, 1966–69	0·108	0·109	0·109	0·109	0·108	0·105	0·107
	Wheat, 1966–69	1·109	0·109	0·110	0·110	0·110	0·107	0·108
	Standard error	0·003	0·002	0·002	0·002	0·002	0·002	0·001
Red-brown earth	Lucerne, 1966–71	0·128[A]	0·132[A]	–	0·124[A]	0·128[A]	0·120[A]	0·112
	Lucerne, 1968–71	0·122[A]	0·124[A]	–	0·112[A]	0·120[A]	0·112[A]	0·106
	Lucerne, 1970–71	0·103	0·112	–	0·106	0·110	0·105	0·105
	Fallow, 1966–71	0·110	0·105	–	0·099	0·103	0·098	0·102
	Wheat, 1966–71	0·112	0·106	–	0·104	0·107	0·102	0·101
	Standard error	0·004	0·005	–	0·004	0·004	0·004	0·003

[A] Lucerne treatments > control treatments ($P<0\cdot05$).

At least 2½ years of lucerne were required to raise the total soil nitrogen above the original level on both soil types. For soil samplings in mid 1970 and mid 1971, there was a close relationship ($P>0\cdot01$) between the level of total soil nitrogen and the length of the lucerne leys (r = 0·98 and 0·99). For every year of lucerne, nitrogen increased by 0·0078% units on the black earth and by 0·0052% units on the red-brown earth (Fig. 2). Increases in total soil nitrogen followed cumulative levels of nitrogen uptake in the lucerne tops, but there were insufficient data to establish correlations.

Significantly higher levels of soil nitrogen were maintained after the longer lucerne treatments throughout the 9 years of measurement on the black earth, but only for 5 years on the red-brown earth. After the longer lucerne leys, the greatest decline in total nitrogen occurred in the first 3 years on the black earth, but it fluctuated from year to year on the red-brown earth. By the last year of the experiment nitrogen had fallen to the original level or lower in all except the long lucerne treatment on the black earth.

Soil Mineral Nitrogen

Soil mineral nitrogen was greater ($P > 0 \cdot 05$) following the intermediate and long lucerne leys than in the cultivation treatments in every year except 1973 and 1977 on the black earth and 1971, 1977 and 1978 on the red-brown earth (Fig. 1). Increases following the short lucerne ley were usually smaller and less frequent. Extended fallowing caused a significant increase in mineral nitrogen only in the first cropping year on the black earth.

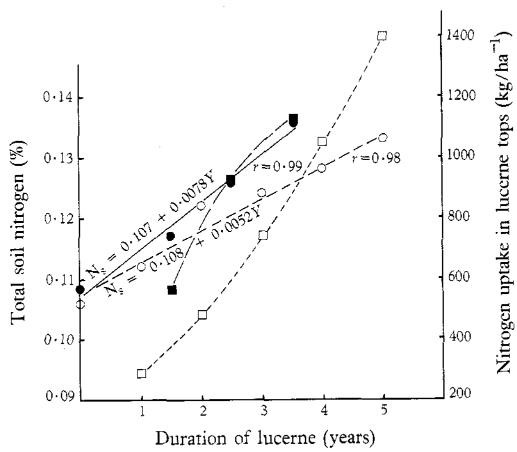

Fig. 2. Total soil nitrogen (N_s) and lucerne nitrogen uptake in relation to duraton of lucerne ley.
●——● Soil nitrogen on black earth. $N_s = 0 \cdot 107 + 0 \cdot 0078 Y$.
○– – –○ Soil nitrogen on red-brown earth. $N_s = 0 \cdot 108 + 0 \cdot 0052 Y$.
■– –■ Lucerne nitrogen on black earth.
□-----□ Lucerne nitrogen on red-brown earth.

Mineral nitrogen levels showed a marked downward trend from 1970 to 1975, after which they remained fairly constant but rose again in 1978 (Fig. 1). This general downward trend was interrupted in 1971 by a precipitous drop in nitrogen caused apparently by very high fallow rainfall (574 mm) and consequent leaching in that year. Large proportions of ammonium in the mineral nitrogen (up to 75% in the lucerne leys on the red-brown earth and about 20% in other treatments) indicated that denitrification also caused significant losses in 1971. The decreases were greater on the red-brown earth, which is more freely draining than the black earth (Holford and Doyle 1978). In spite of this, nitrogen levels following the intermediate and long lucerne leys were higher in 1973 in the red-brown earth, probably because the black earth had been cropped during the previous year. The rise in mineral nitrogen in 1978, after fallow rainfall of 460 mm, indicates that the very low nitrogen in 1976 and 1977 was caused by excessive fallow rainfall (643 and 632 mm respectively) rather than by exhaustion by cropping. Proportions of ammonium-nitrogen fell to less than 10% after 1974, which indicated that losses by denitrification were small during the last 4 years of measurement. Mineral nitrogen levels fluctuated more widely on the red-brown earth than on the black earth, which suggested that under suitable conditions mineralization rates are higher on the red-brown earth, but that potential losses by leaching and plant uptake are also higher.

The trends in mineral nitrogen levels for the periods 1971–1978 on the black earth and 1973–1978 on the red-brown earth (Fig. 1) show a marked similarity to those of nitrogen uptake in the wheat tops for the corresponding periods (Fig. 3 of Holford 1980). In fact, nitrogen uptake for all treatments on both soils ($n = 65$) was closely correlated ($r = 0 \cdot 90$) with mineral nitrogen in the top 15 cm of soil, there being an increase in nitrogen uptake of 6·2 kg/ha per unit increase of soil mineral nitrogen. The correlation was even greater ($r = 0 \cdot 95$) for the red-brown earth data ($n = 30$) alone, but the regression coefficient was the same.

Seasonal Fluctuations in Mineral Nitrogen

In surface soil during 1975. The larger differences in soil mineral nitrogen between treatments in the red-brown earth than in the black earth were probably caused by the 2 years of extra cropping on the latter soil since the termination of the lucerne and fallow treatments (Fig. 3). There was significantly more ($P < 0{\cdot}05$) mineral nitrogen in the intermediate and long lucerne treatments than in the cultivation treatments in most samplings throughout the year. Extra mineral nitrogen in the short lucerne ley was apparently almost exhausted by 1975 in the black earth, but it was significantly greater in the January, April, and December samplings on the red-brown earth.

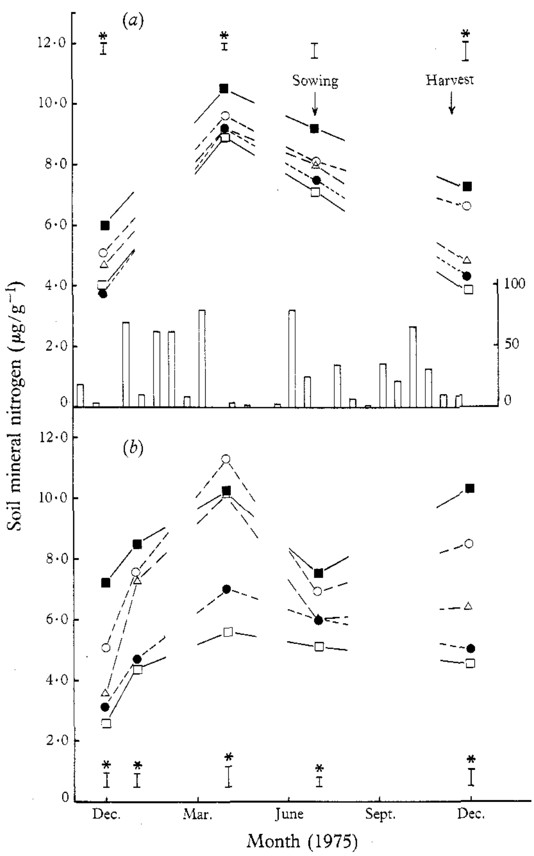

Fig. 3. Seasonal fluctuations in soil mineral nitrogen (0–15 cm) after various periods of lucerne ley, extended fallow, and continuous wheat cropping. Symbols as for Fig. 1. (*a*) Black earth. (*b*) Red-brown earth.

On both soils mineral nitrogen was at a minimum level immediately after wheat harvest in 1974, and it reached a maximum in the following April (Fig. 3). In the red-brown earth it fell steeply in the lucerne treatments, but only slightly in the cultivation treatments, during the next 3 months to sowing. In the black earth there was an almost uniform decline in all treatments between April and December, reaching similar levels in the short lucerne and cultivation treatments as in the previous December, but remaining at higher levels in the longer lucerne treatments. The unusual increase in nitrogen levels in the lucerne treatments during the growing season on the red-brown earth shows that mineralization rates exceeded the rate of uptake by the crop on this soil, and that yields therefore should not have been limited by nitrogen deficiency in 1975. In fact, nitrogen content of the wheat tops was marginal (1·24–1·38%), but grain yields on the short and intermediate lucerne treatments were higher than in any other year (Fig. 2 of Holford 1980).

In subsoil during 1975 to 1977. The marked decline in soil mineral nitrogen in 1971 and the very low levels in 1976 and 1977 suggest an effect of heavy fallow rainfall (>570 mm) in leaching mineral nitrogen from the surface soil (Fig. 1). The much higher grain yields and nitrogen uptake in 1976 on the black earth than on the red-brown earth (Holford 1980) indicated that the movement of nitrogen through the profile may have differed in the two soils. Mineral nitrogen levels were therefore measured at four depths between 15 cm and 100 cm during the fallows of 1975 to 1977 in the continuous wheat and long lucerne treatments.

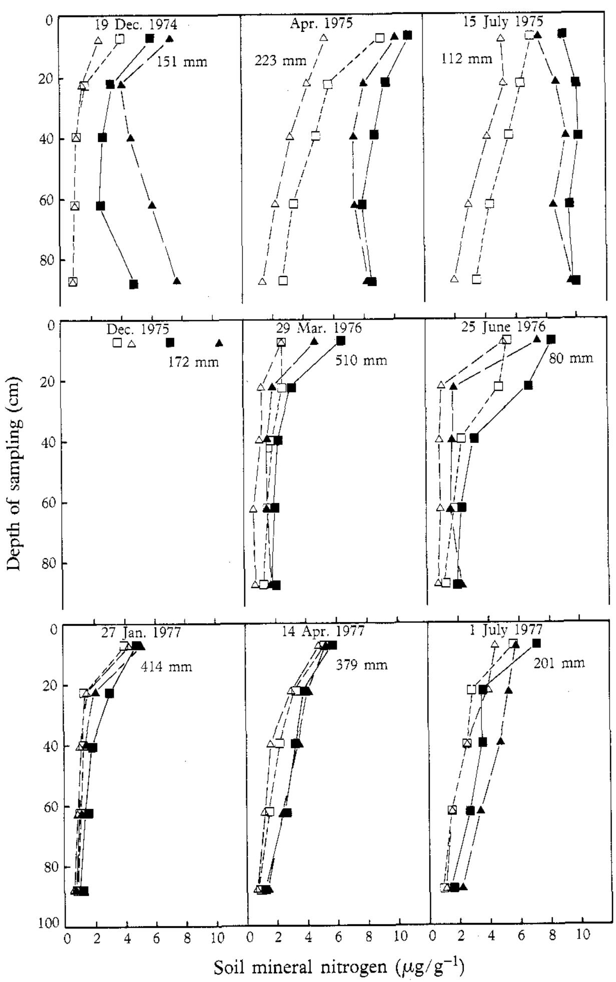

Fig. 4. Soil mineral nitrogen (0–100 cm) during fallowing of a black earth (■ and □) and a red-brown earth (▲ and △) after lucerne (■ and ▲) and continuous wheat (□ and △). For each sampling, rainfall for previous 90 days is indicated.

At the beginning of each fallow, mineral nitrogen was low and more or less uniform in the continuous wheat treatment throughout the subsoil in both soils (Fig. 4). As in the topsoil (Fig. 3) it rose considerably during the next 4 months in 1975, but to a less extent in 1977 and not at all in the very wet fallow of 1976. It continued to rise slightly during the remainder of the fallow in 1975 and 1977, but rose only in the black earth in 1976. In the red-brown earth the potential for mineralization in the subsoil was apparently exhausted by the end of March in 1976. Generally the level of accumulation in the continuous wheat treatment decreased with increasing depth of soil.

Mineral nitrogen was considerably higher in the lucerne treatments than in wheat treatments in both soil types at all depths (Fig. 4). In spite of an extra 2 years of cropping on the black earth since the termination of lucerne, mineral nitrogen tended to be higher in this soil than in the red-brown earth, except at the first sampling in December 1974 and at the last sampling in July 1977. Rainfall during the 3 months prior to each sampling was 151 mm and 201 mm respectively at these two sampling times, whereas at all other sampling times it was either much less (<112 mm) or more (>223 mm). This suggests that the mineralization and retention of nitrogen was more susceptible to extremes of rainfall in the red-brown earth than in the black earth. Under very dry conditions, mineralization was apparently depressed more in the red-brown earth, while under very wet conditions losses of nitrogen by leaching and possibly denitrification were greater in this soil.

The high levels of mineral nitrogen at 75–100 cm depth in December 1974 following relatively dry conditions (538 mm annual rainfall) suggest that in the presence of excess nitrogen following the lucerne treatments, maximum depletion of nitrogen by the crop occurred at shallower depths and particularly at 15–50 cm (Fig. 4). The contrasting situation of decreasing nitrogen levels at increasing depth in January 1977 followed 931 mm of rain in 1976 which, with crop uptake, depleted nitrogen to the full depth of the sampled profile. The uniformly high levels of nitrogen at all depths at the end of the 1975 fallow, which received adequate (410 mm) and well-distributed rainfall, indicates that the beneficial effects of lucerne on mineral nitrogen extended to a soil depth of at least 100 cm. The much lower levels of nitrogen, particularly at 30–100 cm depth, in the following 2 years appear to be the effect more of excess rainfall during the periods of mineralization than of increasing depletion of the soil by cropping. This is borne out by the increase in topsoil nitrogen, particularly in the black earth in 1978 (Fig. 1).

Table 3. Soil mineral nitrogen (kg ha^{-1}) to 100 cm depth through fallows 1975, 1976, and 1977

Soil	Year	Continuous wheat			Long lucerne		
		Start^A	Mid^B	End^C	Start	Mid	End
Black earth	1975	17·6	54·3	58·4	43·8	101	112
	1976		21·4	31·3		32·4	45·5
	1977	18·0	26·4	27·9	24·6	35·1	38·5
Red-brown earth	1975	16·8	40·8	48·3	80·2	108	117
	1976		15·1	20·7		28·5	36·4
	1977	19·5	27·0	32·9	23·4	41·6	54·5

^{A} December or January. ^{B} March or April. ^{C} June or July.

These large variations in subsoil nitrogen from year to year mean that the total mineral nitrogen available to the wheat crop may show little relationship to the mineral nitrogen in the top 15 cm of soil. For example, there was little difference in the topsoil nitrogen at sowing time between 1975 and 1976 (Fig. 2), but if the subsoil nitrogen was taken into account the differences were very large (Fig. 4). When the total mineral nitrogen levels to 100 cm depth are calculated (Table 3), it can be seen that the regular decline in topsoil nitrogen over the 3 year period (Fig. 2) was reflected only in the black earth, and that in the red-brown earth there was a very large decrease in total mineral nitrogen in 1976 but then an increase in 1977. The correlation coefficients for the relationships between nitrogen uptake in wheat tops

(Fig. 3 of Holford 1980) and topsoil mineral nitrogen for the 3 year period ($n = 6$) were 0·91 ($P < 0·05$) for the black earth and 0·74 for the red-brown earth. The corresponding correlations for mineral nitrogen to 100 cm depth were increased to 0·98 ($P < 0·001$) for the black earth and 0·93 ($P < 0·01$) for the red-brown earth, which indicated that the wheat crop was taking nitrogen from a much greater depth than the top 15 cm. These results may also suggest that mineral nitrogen in the top 15 cm of soil is a better index of available nitrogen in a black earth, which is less susceptible to leaching, than in a red-brown earth.

General Discussion

The linear relationships between total soil nitrogen and duration of lucerne ley were very similar to that for subterranean clover on a sandy soil in Western Australia (Watson 1969), the absolute increases in nitrogen for a 3 year period being the same on the black earth but slightly lower on the red-brown earth. However, the much longer beneficial effects of lucerne on the growth of subsequent wheat in the present study (Holford 1980) suggest that the effects of lucerne on soil nitrogen may have extended further into the subsoil than those of subterranean clover (Watson 1963). In addition, the retention of accumulated nitrogen would be greater in these more slowly leaching soils than in the sandy Western Australia soil. For each year of lucerne growth the average increase in total soil nitrogen (0–15 cm), above the level contained in the continuous wheat treatment, was equivalent to about 140 kg nitrogen ha^{-1} in the black earth and about 110 kg nitrogen ha^{-1} in the red-brown earth. For comparison, on black earths from southern Queensland, one experiment recorded an increase of 150 kg nitrogen ha^{-1} (0–10 cm) from 2 years of lucerne ley (Littler and Whitehouse, unpublished data), while a second experiment under drought conditions recorded an increase of only 60 kg nitrogen ha^{-1} after 4 years of lucerne (Lloyd, unpublished data).

The very large increases in soil mineral nitrogen following lucerne clearly demonstrate the nitrogen-fixing ability of this legume when grown in rotation with wheat. The quantities of nitrogen involved are much greater than those previously recorded (Wells 1970) in Australia, and they obviously make a large contribution to the nitrogen nutrition of following wheat crops (Holford 1980; Littler, unpublished data). The greater longevity of legume nitrogen residues on the black earth may be attributed not only to their greater resistance to leaching but also to lower susceptibility to denitrification in the subsoil (Craswell and Strong 1976). On the other hand, proportions of ammonium nitrogen remained between 10 and 20% for 5 years after the lucerne on the black earth compared with only 3 years on the red-brown earth. The benefits to subsequent wheat crops of nitrogen leaching into the subsoil within reach of the root system are well documented (Storrier 1965; Craswell and Strong 1976; Strong and Cooper 1980). On considering the variability in rainfall and consequent degree of depletion of mineral nitrogen during the fallow, it is surprising that there was such a high correlation between topsoil mineral nitrogen and plant uptake over the 8 years of measurement.

All the relevant data from the two experiments demonstrated the overriding effect of excess rainfall on the depletion of mineral nitrogen from the soils, especially during the summer and early autumn when rates of mineralization were greatest. This was particularly evident in 1976 and 1977. Mineral nitrogen was partially replenished in the black earth during the drier conditions of late autumn in 1976, but not in the red-brown earth. There was some evidence that mineralization rates were lower on the red-brown earth during very dry conditions, but possibly higher during moderately moist conditions. As a result of the differences between the two soil types in their susceptibility to extremes of rainfall, mineral nitrogen levels fluctuated more on the red-brown earth than on the black earth, and these were reflected in the nitrogen uptake by wheat (Holford 1980).

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