Chapter 11

THE EFFECT OF TILLAGE ON THE CHEMICAL FERTILITY OF SOIL

A.D. Robson and A.C. Taylor

Soil fertility can be defined as the ability of the soil to produce a commodity that has commercial value (Hallsworth, 1969). This definition, while helpful, has the limitation that the level of inputs required (for example fertilisers to correct nutrient deficiencies or gypsum to alleviate surface crusting) also needs to be considered. There are two other consequences of this definition. Firstly, the assessment of soil fertility will depend on crop species. For example, the supply of nitrogen is not important for growth of nodulated legumes but is a major component of soil fertility for the growth of cereals. Secondly, there are marked interactions between climate (temperature, water supply) and soil fertility. For example, responses in grain yield to soil nitrogen fixed in preceding leys was markedly dependent on rainfall after flowering (Tuohey and Robson, 1980).

The quantitative assessment of soil fertility and the quantitative investigation of tillage and rotation on soil fertility is difficult. In particular there are many components of soil fertility (Table 11.1); effects of management practices on grain yield may reflect synergistic

Table 11.1 Components of soil fertility

Chemical
Nutrient supply
Acidity
Salinity
Physical
Soil strength
Surface crusting
Components affecting water infiltration
Porosity
Biological
Pathogenic fungi
Soil animals
Mycorrhizal fungi
Rhizobium

responses in several components or may represent net effects of opposing responses. For example, during legume leys both water-stable aggregates and soil nitrogen increase (Rowland *et al.*, 1984). Are increased grain yields the result of these changes or are they perhaps due to effects of legume leys on the incidence of nematodes or disease? Another example is the effect of reduced tillage on grain yields. Reduced tillage may increase grain yields by increasing the infiltration of water into soil (Hamblin and Tennant, 1979), while at the same time decreasing the mineralisation of nitrogen (Dowdell and Cannell, 1975) and increasing the incidence of *Rhizoctonia* (R.J. Jarvis and R.F. Brennan, unpublished data). Clearly needed are quantitative relationships between measurements of the components of soil fertility and agricultural production. Ideally these relationships would be obtained with all other components of soil fertility at optimum levels. Moreover, because most changes in soil fertility are gradual there

is a need for well designed, long-term experiments to establish the effects of management practices on the components of soil fertility. These experiments have a rationale different from that of farming-systems research, in which different systems of agricultural production are compared to evaluate their relative profitabilities.

The effects of tillage and residue management on the chemical fertility of soils are largely related to effects on both porosity and the distribution of plant residues and applied fertilisers (Figure 11.1). Surface-retained residues also modify the water and temperature regime at the soil surface. These effects lead to a changed soil micro-environment (Table 11.2)

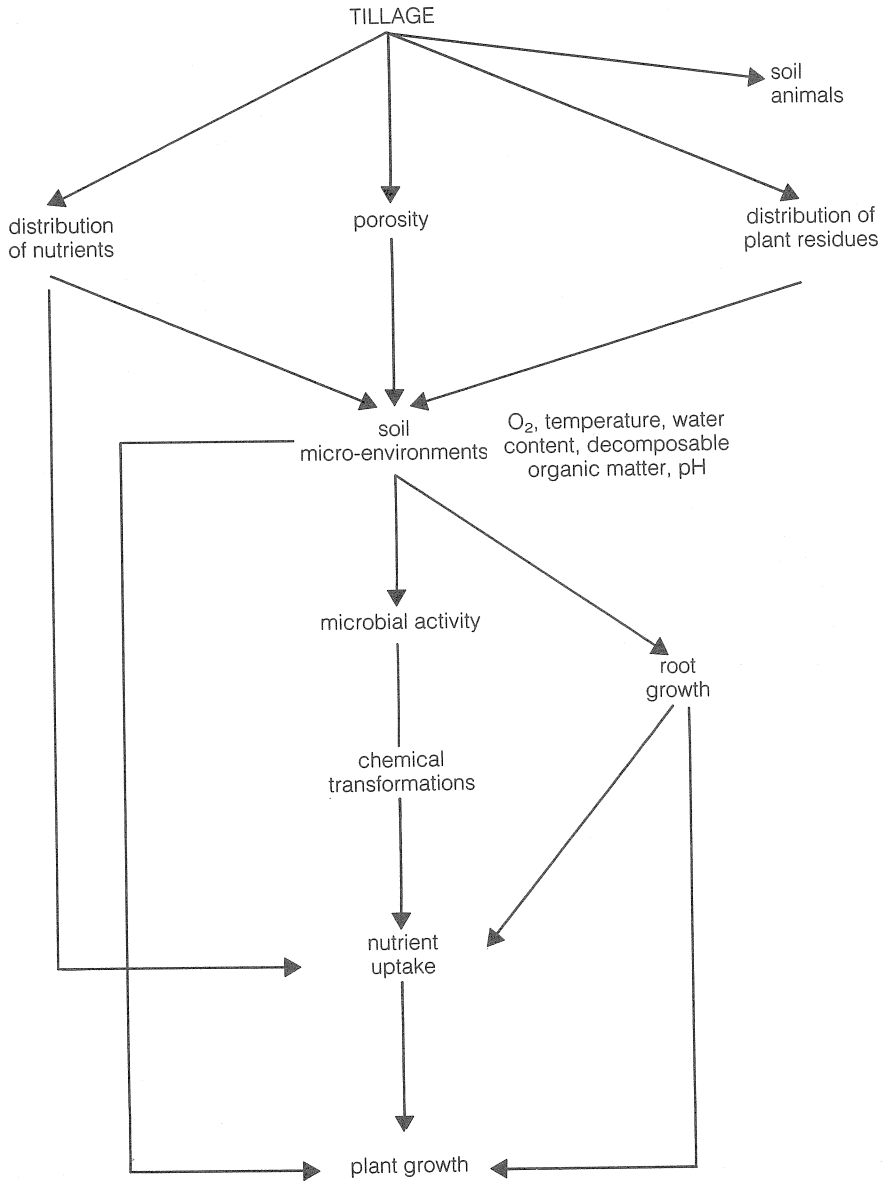

Figure 11.1 Effects of tillage on processes affecting nutrient uptake by plants

with consequences for microbial growth and activity (Table 11.3), chemical transformations of nutrients within soil, root growth and nutrient uptake by plants. This review covers the effects of tillage and residue management on the cycling of nitrogen in soil, on the uptake of other nutrients and on soil pH.

Table 11.2 Effect of cultivation on the water content and porosity of the seedbed zone of four Western Australian soils (Hamblin and Tennant, 1979)

Site	Rotation before cultivation	Porosity ($cm^3\ cm^{-3}$) P	Porosity ($cm^3\ cm^{-3}$) Z	Moisture ($cm^3\ cm^{-3}$) P	Moisture ($cm^3\ cm^{-3}$) Z
Mt Barker	Pasture	0.65[a]	0.56	0.252[a]	0.349
Boddington	Pasture	0.60[a]	0.55	0.110[a]	0.178
Wongan Hills	Crop	0.51[a]	0.46	0.078[a]	0.110
Avondale	Crop	0.52	0.54	0.094	0.084

P = Disc ploughed to a depth of 8 cm, worked back with a scarifier, seeded with a tined combine-drill.
Z = Sprayed with 2 L ha^{-1} paraquat–diquat mixture, planted with triple-disc drill with soil in drill slots disturbed to 3 cm.
[a] Difference significant, $P < 0.05$.

Table 11.3 The effect of ploughing on microbial populations for two soil depths at six locations in the United States (Doran and Power, 1983)

Population	Ratio (number in no-tillage treatment to number in ploughed treatment) Soil depth (cm) 0–7.5	7.5–15
Total aerobes	1.32	0.73
Fungi	1.49	0.77
Actinomycetes	1.20	1.00
Bacteria	1.36	0.69
Aerobic nitrifiers	1.03	0.49
Facultative anaerobes	1.59	1.18
Denitrifiers	2.70	1.92

EFFECTS OF TILLAGE, RESIDUE MANAGEMENT AND ROTATION ON CYCLING OF NITROGEN IN SOILS

The accretion and decomposition of organic matter and nitrogen in Australian soils under a variety of rotations have been reviewed extensively (for example Greenland, 1971; Clarke and Russell, 1977; Russell, 1981; Russell and Williams, 1982; Ladd and Russell, 1983). This review concentrates on how tillage practices interact with rotation to affect the cycling of nitrogen (Figure 11.2).

The accretion of organic matter under pastures has been studied extensively for both temperate and tropical pastures (see reviews by Clarke and Russell, 1977; Ladd and Russell, 1983), with most attention being directed towards the accretion of nitrogen. Within a soil type, the ratio of C:N:S:P in the accreted organic matter appears to be quite constant (Williams and Donald, 1957). The major factor affecting the accretion of nitrogen appears to be the amount of legume growth (Crack, 1972). For example, in many situations the accretion of nitrogen was increased by

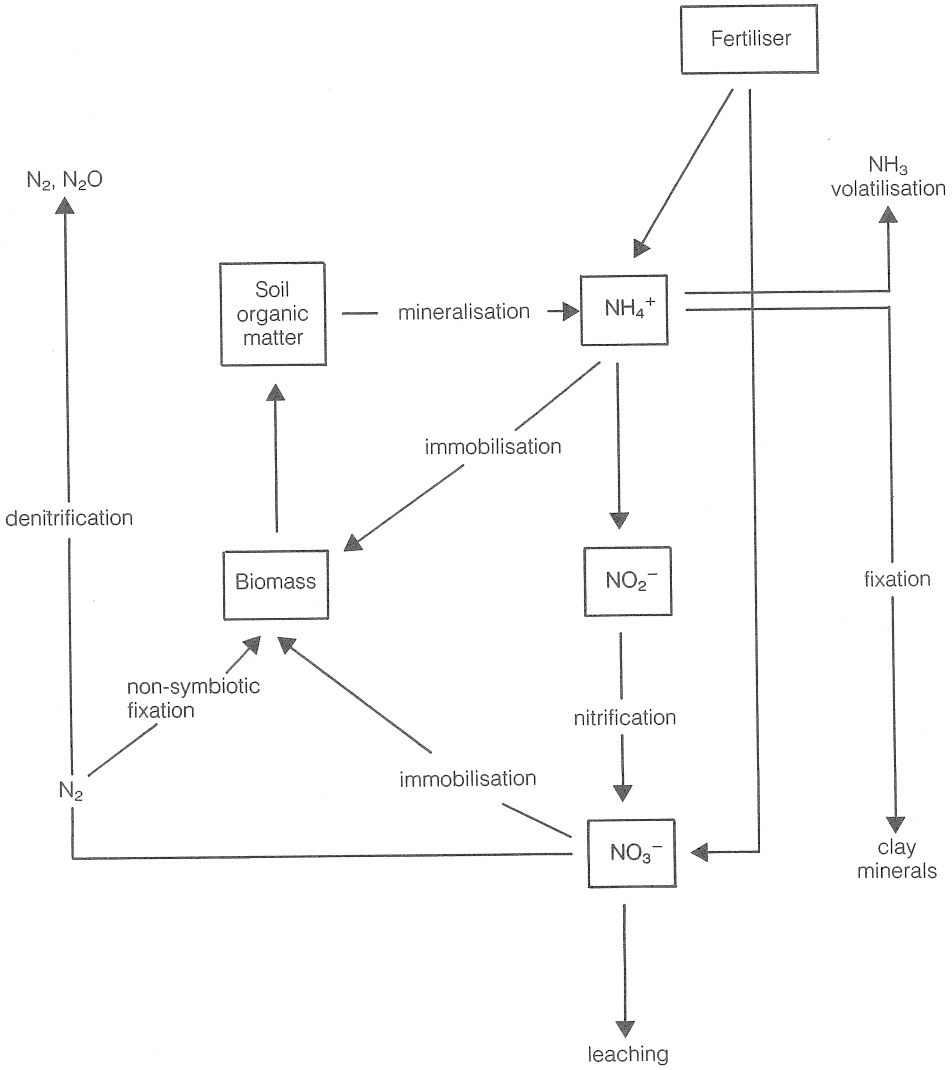

Figure 11.2 Processes in the cycling of nitrogen in soils

the application of phosphatic fertilisers, which increased the production of dry matter by pasture legumes (see review by Robson, 1984).

The increasing production of grain legumes, particularly chick pea (*Cicer arietinum*), lupin (*Lupinus angustifolius*), field pea (*Pisum arvense*) and soybean (*Glycine max*) in Australia, has focused attention on the effects of these crops on nitrogen supply for subsequent cereal crops. Enhanced cereal yields after grain legumes may reflect both enhanced nitrogen supply and other effects (for example decreased root disease, Clarke, 1984). There have been very few studies of the rates of nitrogen fixation under grain legumes in the field, the extent of removal of that nitrogen in seed and the rates of nitrogen release from residues of grain legumes. It is important that such studies be conducted with a range of legumes, tillage practices and residue management.

The decline in organic matter with cropping has also been extensively studied (see reviews by

Greenland, 1971; Clarke and Russell, 1977). Most attention has focused on nitrogen. Where the original C:N ratios were less than 15:1 cropping had little effect on the ratios of C:N:S:P in soil organic matter (Russell and Williams, 1982). However, the red-brown earths of southern New South Wales retained relatively more organic phosphorus than organic nitrogen or carbon when cropped (Williams and Lipsett, 1961).

There have been many attempts to describe quantitatively the effect of rotation on changes in organic nitrogen levels in soils (see Russell, 1981). A recent model (Russell, 1975; 1981) can be represented by the equation:

$$dN/dt = -K_1 tN + K_2 + K_3(t)Y(t)$$

where $K_1(t)$ is a decomposition constant, at time t, that indicates the proportion of organic nitrogen (N) mineralised, and this coefficient may vary with rotation and tillage; K_2 represents a constant addition from non-crop sources, particularly the contributions made by free-living microorganisms; $Y(t)$ is the amount of dry matter produced and $K_3(t)$ is a coefficient that indicates the proportion of dry matter retained in the soil as organic nitrogen. This model is useful in that effects of tillage on each of the coefficients can be examined separately.

Effects of tillage

Most of the effects of tillage on nitrogen cycling operate via effects on the amount of organic nitrogen mineralised. Declines in soil nitrogen with wheat-fallow rotations were much greater for ploughed soils than for uncultivated soils (Fleige and Bauemer, 1974; Fenster and Peterson, 1979; Lamb *et al.*, 1985). Indeed, for uncultivated soils in some situations in north America there was less than a 2% decline in soil nitrogen after six crops whereas, for ploughed soils, soil nitrogen had declined by more than 15% (Lamb *et al.*, 1985). In this study there was much greater leaching of nitrate beyond the root zone on the ploughed soils than in the uncultivated soils.

Nitrate levels can be higher (Kohn *et al.*, 1966; Thomas *et al.*, 1973); Blevins *et al.*, 1977; Dowdell and Cannell, 1975), similar (Cooke *et al.*, 1985) or lower (Reeves and Ellington, 1974) where the soil is cultivated before sowing rather than left undisturbed. This variation in response to ploughing may reflect variable effects of ploughing on nitrification, denitrification and leaching of nitrogen depending upon soil temperature and water supply. Additionally, initial effects of cultivation in enhancing nitrate levels in soils as compared with uncultivated soils may decrease with time. For example, nitrate levels in ploughed soils were 40% greater than those in uncultivated soils in the early years of a continuous cropping experiment in North America (Lamb *et al.*, 1984). After 14 years there was little difference in nitrate levels between cultivated and uncultivated soils.

Cultivation may (Davies and Cannell, 1975) or may not (Reeves and Ellington, 1974; Rowell *et al.*, 1977) influence the response of grain yield to applied nitrogen. In one-third of a large number of comparisons in the United Kingdom, cereals grown without tillage required more fertiliser nitrogen than cereals grown after ploughing (Davies and Cannell, 1975). In some Western Australian situations, grain yield was depressed in uncultivated soils at low rates of applied nitrogen but was greater in uncultivated soils at high rates of nitrogen supply (Figure 11.3) (Jarvis *et al.*, 1985).

Depressed early growth of direct drilled cereals, which has been widely observed even where nitrate levels at sowing are similar, may (Cooke *et al.*, 1985) or may not (Reeves and Ellington, 1974; Rowell *et al.*, 1977) lead to reduced grain yield.

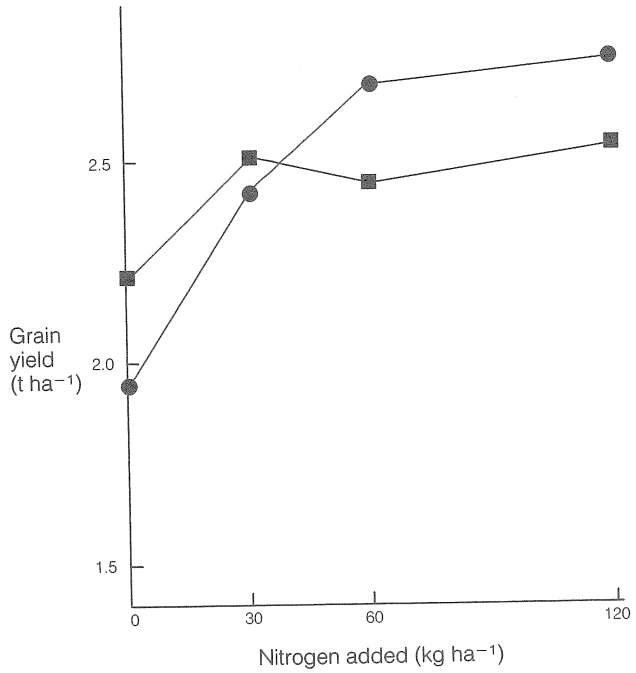

Figure 11.3 The responses of wheat to nitrogen for direct drilled (●) and for wheat grown after ploughing (■) at Avondale, Western Australia (Jarvis *et al.*, 1985)

The effect of tillage on nitrogen transformations within soil are complex because of the large number of soil properties changed by tillage. For example, ploughed soils are generally warmer, drier and better aerated for a time than uncultivated soils. Additionally, ploughed soils may be less acidic (see later) and have lower contents of decomposable carbon substrates for microbial growth. For most transformations of nitrogen in soil (Figure 11.2) there are optimum conditions of temperature, water content, aeration and pH for maximum rates of reaction. Hence the effects of tillage on denitrification, mineralisation, immobilisation and nitrification will depend on the effect of tillage on soil conditions relative to those optimum values.

Denitrification is generally greater in uncultivated soils than in ploughed soils (Doran, 1980; Burford *et al.*, 1981). There are several possible mechanisms. Denitrification is most rapid under anaerobic conditions (Firestone, 1982; Mosier *et al.*, 1985) in soils with high amounts of carbon substrates for the growth and activity of denitrifying microorganisms (Burford and Bremner, 1975; Craswell and Martin, 1975). In contrast, rates of mineralisation of organic nitrogen and of nitrification are frequently greater in ploughed soils than in uncultivated soils (Dowdell and Cannell, 1975) largely because of the greater aeration of ploughed soils and the greater exposure of less accessible substrates to microorganisms.

Effects of tillage on rates of denitrification and nitrification may be different at different soil depths (Groffman, 1984). In the surface 5 cm both nitrification and denitrification activity were greater in uncultivated than in cultivated soils. However, in the 5-13 cm layer both nitrification and denitrification activity were greater in cultivated soils than in uncultivated soils. In another situation the number of denitrifiers was greater in both the 0-7.5 cm and 7.5-15 cm layers in uncultivated soils than in cultivated soils (Table 11.3) (Doran and Power, 1983). However, in this study there was no effect of tillage on the number of aerobic nitrifiers in the top 7.5 cm but a large effect of ploughing in increasing the number of aerobic nitrifiers in the 7.5-15 cm layer.

Withholding cultivation from soils subject to periodic waterlogging (Anon., 1980) is likely to increase denitrification near or below the surface (McGarity and Myers, 1968).

Although increased nitrate concentration in ploughed soil may reflect both decreased denitrification and increased mineralisation, the latter may be more important because of the absence of suitable conditions for denitrification in many situations. For example, nitrate concentrations were greater in ploughed soils in plots with and without mole drainage (Dowdell *et al.*, 1983).

In many uncultivated soils the amount of potentially mineralisable nitrogen (Stanford and Smith, 1972; 1976) may be considerably greater than in ploughed soils (Doran, 1980; Broder *et al.*, 1984). In general this reflects less aeration and substrate exposure (Dowdell and Cannell, 1975) and a greater immobilisation of nitrogen in microbial biomass in uncultivated soils (Lynch and Panting, 1979; Doran and Power, 1983).

The increased microbial activity in uncultivated soils is reflected by greater urease activity in pasture than in cultivated soils (O'Toole *et al.*, 1985) and by greater urease and phosphatase activities in uncultivated than in cultivated plots (Sequi *et al.*, 1985). In the latter study there were strong but separate correlations within cultivated and uncultivated soils between urease activity and the number of pores in the 30-200 μm range.

Under Australian conditions there have been relatively few studies of the effect of tillage on nitrogen transformations in soils.

Fallowing, by increasing the mineralisation of organic nitrogen, may lead to more rapid declines in soil nitrogen than continuous cropping (Russell, 1981; Table 11.4; Biederbeck *et al.*, 1984). Fallowing almost doubled the proportion of total soil nitrogen present as nitrate-nitrogen at sowing (French, 1978). Elsewhere, fallowing has decreased organic carbon levels, microbial biomass and potentially mineralisable nitrogen (Biederbeck *et al.*, 1984). Nitrate released by fallowing may be leached from the root zone in coarse-textured soils. Moreover, fallowing may also increase losses of nitrogen because of greater erosion of soil from a cultivated surface. Similar amounts of mineral nitrogen accumulated under fallows maintained free of weeds either by cultivation or herbicides (Kohn *et al.*, 1966; Cooke *et al.*, 1985).

Table 11.4 The effect of crop rotation on chemical and biological properties of soils after 16 years (Biederbeck *et al.*, 1984)

Property	Fallow wheat	Continuous wheat
Organic carbon (%)	1.94	2.15
Total nitrogen (%)	0.20	0.23
Microbial biomass:		
Carbon ($\mu g\ g^{-1}$ soil)	216	260
Nitrogen ($\mu g\ g^{-1}$ soil)	62	65
Cumulative respiration ($\mu g\ CO_2\ g^{-1}$ soil)	92	138
Potentially mineralisable nitrogen ($\mu g\ g^{-1}$ soil)	159	230

Effects of residue management and rotation

Residues of crops and pastures can be burnt, incorporated into the soil or left on the surface.

There have been relatively few studies of the long-term effects of alternative practices on the chemical fertility of soils. In general, effects of burning of residues on levels of soil nitrogen are small and much less than effects on levels of organic carbon (Table 11.5). Sometimes, the faster rundown of soil nitrogen where residues are burnt or removed rather than incorporated (Hooker *et al.*, 1982) takes more than a decade to be transmitted into lower wheat yield (Hooker and Schepers, 1984). Residues retained on the surface of soils are likely to decompose more slowly than those incorporated into soil, largely because of less favourable water contents. However, after 5 years of retention of cereal residues there were only slight differences in organic carbon levels between cultivated and zero-tillage plots (Loch and Coughlan, 1984).

Table 11.5 Effects of the burning of residues on the concentrations of total nitrogen, nitrate-nitrogen, mineralisable nitrogen and organic carbon in soils

Measurement	Years before measurement	Depth (cm)	Stubble burnt	Stubble retained	Reference
Total nitrogen (%)	5	0–10	0.10	0.10	Loch and Coughlan (1984)
Total nitrogen (%)	12	0–15	0.094	0.098	Rooney *et al.* (1966)
Total nitrogen (%)	19	0–15	0.46	0.49	Biederbeck *et al.* (1980)
NO_3-N at seeding ($\mu g\ g^{-1}$)	12	0–15	14.0	9.7	Rooney *et al.* (1966)
Potentially mineralisable N ($\mu g\ g^{-1}$)	19	0–15	53	59	Biederbeck *et al.* (1980)
Organic carbon (%)	5	0–10	1.59	1.70	Loch and Coughlan (1984)
Organic carbon (%)	19	0–15	4.5	5.2	Biederbeck *et al.* (1980)
Organic carbon (%)	15	0–15	1.97	2.29	Undersander and Reiger (1985)

Decomposition of both crop and pasture residues follows a similar pattern (Ladd *et al.*, 1981) with an initial rapid loss followed by a more gradual decline. The release of carbon from plant residues appears to be largely unaffected by the ratio of carbon to nitrogen in the residues and to be similar for residues of different species and origins (Ladd and Russell, 1983).

Differences in the proportion of carbon lost in the rapid phase from decomposing plant parts of legumes (leaves > stems > roots) were due mainly to differences in amounts of readily metabolisable components (Amato *et al.*, 1984). Drying and rewetting promoted decomposition of pods, leaves, stems and roots of strand medic (*Medicago littoralis*) - the more frequent the drying and wetting cycles, the greater the decomposition (Amato *et al.*, 1984).

In general, the rates of decomposition of plant residues in soils are proportional to the amounts of, for example, barley straw (Sorenson, 1963) and medic residues (Ladd *et al.*, 1983b) added. However, in one study, increasing the amount of legume residue added increased only slightly the extent of decomposition (Ladd *et al.*, 1983b), perhaps reflecting a limit on the number of sites available for the protection and stabilisation of organic residues (as suggested by Jenkinson, 1977).

The effect of the decomposition of plant residues on levels of mineral nitrogen in soils is

closely related to the ratio of carbon to nitrogen in those residues (Parr and Papendick, 1978; Ladd and Russell, 1983). In the short term, the incorporation of cereal residues (high C:N ratio) into soil can markedly decrease the availability of nitrogen to plants by increasing the immobilisation of soil and fertiliser nitrogen (see for example Craswell, 1978; Bacon, 1982; Saffigna *et al.*, 1984). Immobilisation of nitrogen by the incorporation of cereal residues may reduce wheat yield in soils with low nitrogen reserves (Rooney *et al.*, 1966), but have no effect where soil nitrogen is higher (Hooker *et al.*, 1982). Incorporation of legume residues into soil released mineral nitrogen for uptake by wheat (Ladd *et al.*, 1981; 1983a). In these two studies over several seasons and sites, wheat recovered from 10.9 to 27.8% of the nitrogen added in the legume residues. Uptake of nitrogen from legume residues by two successive wheat crops was approximately proportional to the input of nitrogen in the residues (Ladd *et al.*, 1983a).

When the incorporation of cereal residues results in net immobilisation, several important consequences must be considered. Frequently, crops grown after burning residues yield more than crops where residue is incorporated (see for example, Rooney *et al.*, 1966).

Secondly, it may be desirable to delay the application of nitrogenous fertiliser until after the cereal residues have decomposed. The amount of nitrogen in microbial biomass reached a maximum 48 days after the addition of cereal straw; nitrogen in urea applied 129 days after the addition of the straw was not immobilised (Dalal and Strong, 1984).

It has been suggested that while retention of residues leads initially to immobilisation of soil nitrogen in microbial biomass, eventually a new equilibrium will be attained where retention of residues does not lead to increased requirements for nitrogen fertiliser. There is little evidence to support this suggestion. Indeed in south-east Queensland retention of residues led to greater requirements for nitrogen than burning of residues even after 10 years of treatments (Littler and Marley, 1978).

The retention of cereal residues may increase nitrogen fixation by non-symbiotic microorganisms. The incorporation of straw into an alkaline soil increased the amount of nitrogen fixed as assessed using the acetylene reduction assay (Roper, 1983). Increasing the amount of straw incorporated increased the rate of acetylene reduction. There was a close correlation through time between rate of acetylene reduction and rate of straw decomposition. Rates of acetylene reduction were greatest in soils at and above field capacity and decreased as the soils dried out (Roper, 1983; 1985). It is not yet possible to quantify the gains made by non-symbiotic nitrogen fixation associated with straw retention, but they are only likely to be significant in summer-rainfall areas where soil water and temperature are likely to favour it for relatively long periods.

Tillage and residue management may markedly affect the establishment and growth of legume pastures following cereal crops. This area has received little study in Australia despite the widespread use of legume-ley rotations and the close relationship between nitrogen inputs and legume growth. Tillage and residue management may affect the establishment and growth of legume pastures in several ways. Firstly, retention of cereal straw may decrease the establishment of pasture legumes by decreasing soil-temperature fluctuations and hence decreasing the breakdown of hard seeds. Secondly, the products of decomposition of cereal straw may be toxic to pasture legumes and, finally, straw may be a physical impedance to the emerging legume seedling. Effects of tillage on the establishment of pasture legumes may operate on both the legume and the associated *Rhizobium* bacteria. Cultivation may increase the establishment of legumes by enabling the burial of burrs and seeds leading to more germinable seeds (greater seed production, more rapid breakdown of hard seeds) at the beginning of the growing season. However, cultivation that mixes less acidic surface soil (Jarvis and Robson, 1983; Coventry *et al.*, 1985) with the rest of

the soil may decrease *Rhizobium* numbers (Coventry *et al.*, 1985). Crop establishment using either a cultivated seedbed or direct drilling decreased the pH of the surface soil and decreased *Rhizobium* numbers (Coventry *et al.*, 1985).

EFFECTS OF TILLAGE AND RESIDUE MANAGEMENT ON UPTAKE OF NUTRIENTS OTHER THAN NITROGEN

Tillage can affect the availability of nutrients to plants in several ways. Firstly, tillage can affect the amount and distribution of roots within soil (for example Drew and Saker, 1978). Many of the effects of tillage on root growth are related to effects on the physical micro-environment of the soil (aeration, bulk density, water availability). These effects of tillage have been discussed elsewhere in this monograph (Chapter 6). However, some effects of tillage on the distribution of roots may be due to effects on the chemical micro-environment of the soil.

Secondly, tillage can affect the amount and distribution of nutrients in soil (Figure 11.4) (Drew and Saker, 1978) in several ways (Figure 11.1). Physical mixing of surface-applied nutrients throughout soil can either increase or decrease nutrient uptake by plants depending on the relative magnitude of two opposing effects. Mixing may increase the extent of reactions between applied nutrients and inorganic constituents of soil, which decrease the availability of nutrients to plants. Mixing may also increase the amount of contact between roots and applied nutrients, which increases the availability of nutrients to plants. Apart from effects associated with mixing, tillage can influence the soil micro-environment and thus affect reactions between nutrients and inorganic constituents of soils as well as mineralisation/immobilisation of nutrients from soil organic matter.

Thirdly, tillage and rotation can have marked effects on the abundance and activity of soil fauna (for example Ehlers, 1975) and vesicular-arbuscular mycorrhizal fungi (for example Kruckelmann, 1975). Soil fauna can affect nutrient uptake by mixing nutrients within soils and by increasing the rate of breakdown of plant residues. Mycorrhizal fungi may increase nutrient uptake primarily by shortening the distance that nutrients must diffuse in soil to plant roots (Abbott and Robson, 1984).

EFFECTS ON AVAILABILITY OF NUTRIENTS FOR PLANTS

In some situations, tillage may affect the amount of extractable nutrients in the entire rooting zone of plants. Two effects may be important. Firstly, the absence of mixing may decrease the extent of reactions between nutrients and soil constituents. For example, direct drilling for 4 years enabled a greater accumulation of extractable phosphorus in a soil profile to 50 cm than did ploughing (Drew and Saker, 1980). Similarly, cultivation after many years of broadcast applications of superphosphate to pastures may decrease the availability of the residual phosphorus to plants. Uniform mixing of the surface 10 cm of pasture soils decreased the uptake of phosphorus by plants compared with those grown in undisturbed cores (Williams and Simpson, 1965). Sorption of applied phosphate by the surface 2.5 cm of these soils was much less than that by the 2.5-10 cm layers.

A second effect of tillage on the amount of extractable nutrient may be mediated by effects on soil pH. For example, the surface 30 cm of ploughed soils contained greater amounts of

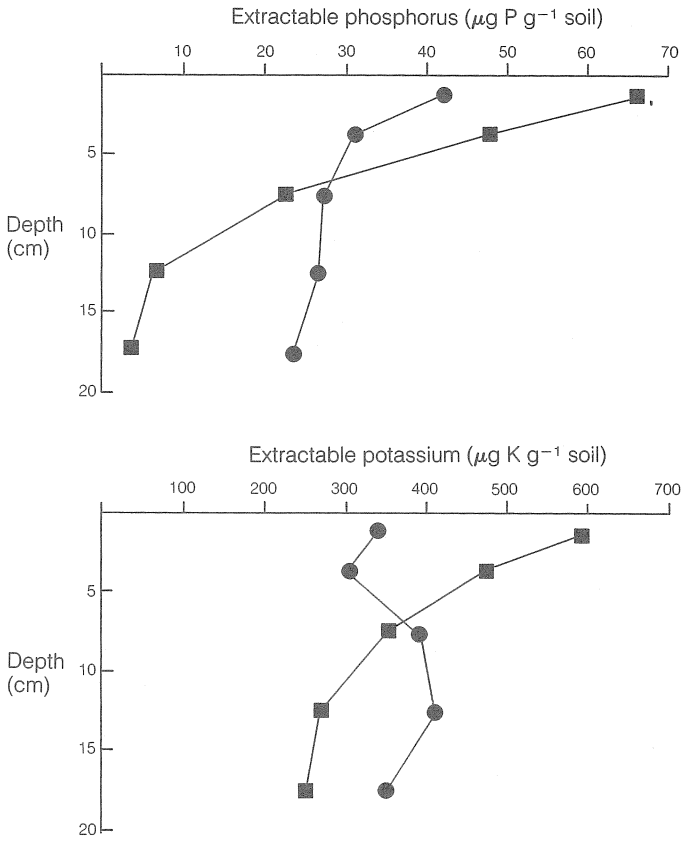

Figure 11.4 Distribution of extractable phosphate and potassium with depth in ploughed (●) and direct drilled (■) soils after 4 years of treatment (Drew and Saker, 1978)

DTPA-extractable iron and manganese than plots that had not been ploughed (Mahler *et al.*, 1985b). These effects of tillage on the amount of extractable manganese and extractable iron were closely correlated with effects on soil pH.

For many nutrients the distribution of chemically extractable nutrients with depth is changed in a similar way by tillage. Without tillage, the concentrations of extractable potassium, phosphorus (Shear and Moschler, 1969; Triplett and Van Doren, 1969; Drew and Saker, 1978; 1980), copper, zinc, manganese, iron (Mahler *et al.*, 1985b) and boron (Mahler *et al.*, 1985a) are higher in the surface 7.5 cm layer and lower in deeper layers than the concentrations after ploughing.

Effects of tillage on the distribution of most of these nutrients do not appear to be associated in many instances with effects on the uptake of nutrients by plants. Nutrient concentrations and contents are frequently similar in crops grown with or without tillage (see for example Shear and Moschler, 1969; Triplett and Van Doren, 1969). There are probably several reasons why this is so. Firstly, the effect of tillage on distribution of roots with depth appears to closely match the effects on distribution of nutrients (Drew and Saker, 1980). Secondly, most comparisons have been made in moist environments where drying out of the surface layers for long periods is unlikely to occur (see for example Cannell and Graham, 1979; Drew and Saker, 1980). Thirdly, many of the comparisons have involved nutrients that are readily retranslocated within

the plant from old leaves to new growth and from vegetative growth to grain. For such nutrients (e.g. phosphorus, potassium), a short period when surface layers are too dry for nutrient uptake may not have marked effects on plant growth. For nutrients that are either immobile (for example calcium, boron) or variably mobile (for example copper, zinc) continuity of supply is essential for growth not to be limited (Loneragan *et al.*, 1976). Finally, many of these comparisons have been conducted at high levels of nutrient supply (for example Estes, 1972). At high levels of nutrient supply, changes in the availability of nutrients to plants may not be reflected in marked effects on nutrient uptake.

There is a need to examine the effect of tillage practices on nutrient requirements in a wider set of environments.

In one study in southern New South Wales, when no phosphate was applied, crops grown after ploughing yielded much more than crops direct drilled (P.S. Cornish, personal communication). At high rates of phosphate application there was no effect of tillage practice on grain yield.

Cultivation may increase the availability of applied nutrients to plants by increasing the amount of contact between roots and the nutrient. Effects of cultivation on the availability of applied copper to plants will be considered here as the effects have been studied extensively.

Irrespective of the source of copper applied, copper is retained in the immediate vicinity of the granule. Even after leaching with 90 cm of water, copper in a surface application of copper-enriched superphosphate was retained within 5 mm of the surface of a sandy soil (Gilkes *et al.*, 1975). Moreover, only plants growing from seeds placed within 2 cm of a granule of copper-enriched superphosphate obtained any copper from the granule after 45 days growth (Gilkes and Sadleir, 1979). It is therefore not surprising that cultivating the soil nine times after the application of copper more than doubled the copper concentrations in barley leaves (Gartrell, 1981). Additionally, five times as much copper had to be applied in large granules of copper-enriched superphosphate (> 3 mm diameter) to equal the effectiveness of small granules (< 1 mm diameter) for copper uptake (Gartrell, 1981). The immobility of copper in soil can lead to situations where surface-applied copper or copper drilled with the seed does not correct copper deficiency. For example, where the surface soil dries out, copper retained in surface layers will not be available to plants (Grundon, 1980).

The immobility of copper within soils also has implications for the residual value of applied copper. The amount of copper applied to correct a deficiency is very much greater than that removed in crop and animal products (Reuter, 1975; Gartrell, 1981). Because subsequent mixing by cultivation increases the number of fertilised sites within soil, the availability of copper to plants may increase with time (Robson *et al.*, 1984). Therefore the increase in positional availability of the applied copper is greater than the decrease in availability associated with chemical reactions between applied copper and soil constituents (Brennan *et al.*, 1980; 1983; 1984). In well mixed soils there appears to be a linear decline in the availability of copper to plants with time of contact between applied copper and soil (Brennan *et al.*, 1985) indicating an eventual need for the reapplication of copper.

When considering the effects of cultivation on the availability of applied nutrients to plants the most important factor to be considered appears to be the nature of chemical reactions between the nutrient and soil constituents. Applied copper reacts strongly with soil constituents, restricting its mobility in soil but not its availability to plants. Phosphate applied to soil may also react with soil constituents but with consequent reductions in availability to plants. Hence the most important factor involved in differences in efficiency of

recovery of fertiliser phosphate from different placements of fertiliser is usually the adsorption capacity of the soil for phosphate (Anghinoni and Barber, 1980).

EFFECTS ON FORMATION OF VESICULAR-ARBUSCULAR MYCORRHIZAS

Effects of tillage on nutrient uptake may operate through effects on the formation of vesicular-arbuscular (VA) mycorrhizas. The magnitude of the effect of mycorrhizas in increasing the uptake of nutrients by plants varies with the level of infection in the roots. Rapid and extensive infection appears to be essential for the maximum benefit to be obtained from this symbiosis (see Abbott and Robson, 1982). One factor that appears to be important in affecting the rate and extent of mycorrhizal infection is the number of infective propagules. However, effects of agricultural practices on mycorrhizal infection can reflect both effects on propagule formation and survival and effects on the formation of infection, which includes the growth of roots. Effects of increasing intensity of cultivations in decreasing mycorrhizal infection in dry beans appeared to be associated with increased soil compaction and decreased root growth (Mulligan *et al.*, 1985).

Different tillage methods appear to have smaller effects on the number of spores of VA mycorrhizal fungi than on the distribution of spores with depth. While there were similar numbers of spores in the top 15 cm of soil under wheat crops grown continuously with either disc ploughing or with direct drilling, there were fewer spores in the top 8 cm and more spores in the 8-15 cm layer in ploughed plots than in those with direct drilling (Smith, 1978b). In an earlier study, Kruckelmann (1975) found more spores in the topmost 7 cm of soil under direct drilled plots than in soil that had been ploughed. Herbicides commonly used to control weeds in minimum tillage systems do not appear to inhibit either the growth of mycorrhizal fungi or mycorrhizal infection when used at recommended rates (see reviews by Smith, 1978a, Trappe *et al.*, 1984).

Fallowing may markedly decrease the number of infective propagules of VA mycorrhizal fungi (Black and Tinker, 1979) because of the absence of host plants and the failure of the propagules to persist for the duration of the fallow. Fallowing may also increase the extent of wind erosion, which may lead to the loss of mycorrhizal propagules, which occur mainly in the surface layers of soil. Eroded soils are usually sites with low infectivity of mycorrhizal fungi (for example Hall, 1980).

Because some agricultural plants do not form mycorrhizas (for example species in the Chenopodiaceae and Brassicaceae families, *Lupinus* species), rotation may markedly influence the extent of mycorrhizal infection. For example, mycorrhizal infection and spore numbers are decreased by the growth of non-mycorrhizal crops such as *Brassica* species (Hayman *et al.*, 1975; Ocampo, 1980; Powell, 1982).

Rotation of mycorrhizal crops may also affect levels of mycorrhizal infection. Kruckelman (1975) found three times as many spores of VA mycorrhizal fungi after 16 years of wheat monoculture than after 16 years of monoculture of rye (*Secale cereale*) or maize (*Zea mays*). At three of four sites in a Mediterranean environment, spore numbers were greater after legume-based pastures than after wheat (Smith, 1980). In a tropical environment, mycorrhizal infection was greater in cassava (*Manihot esculenta*) grown after a legume crop than in cassava grown after a cassava crop (Sieverding and Leihner, 1984). These effects of crop rotation on mycorrhizal infection probably reflect differences in both root growth and the proportion of root length infected among crops.

EFFECTS ON SOIL FAUNA

Invertebrates and earthworms may be very important in the cycling of nutrients (Hutchinson and King, 1982). Many studies have demonstrated greater numbers of earthworms and arthropods in uncultivated than in ploughed soils (see Chapter 12). The effects of these greater numbers on the physical structure of the soil has been clearly demonstrated (Chapter 6), but effects on chemical fertility of soils have not been as clearly established. While the concentrations of plant nutrients are usually greater in the casts of earthworms than in the bulk soil, this may reflect the selection by the earthworms of soil rich in organic matter (Barley and Jennings, 1959). In New Zealand pastures, the release of inorganic phosphorus from earthworm casts was about four times greater than that from surface soil (Sharpley and Syers, 1977).

Because of the marked effects of agricultural practices on the abundance of invertebrates there is a clear need to evaluate quantitatively their role in nutrient cycling.

EFFECTS ON SOIL ACIDITY

Effects of tillage, rotation and residue management on soil pH could result from effects on (i) the amount and distribution of organic matter; (ii) the transformations of nitrogen in soil; (iii) the uptake of cations relative to anions by plants; and (iv) the return of cations relative to anions in plant residues. Processes in soils affecting the acidification and alkalinisation of soils have been reviewed extensively (Helyar, 1976; Bache, 1980; Van Breeman *et al.*, 1983; Rowell and Wild, 1985).

An important consideration is that proton-producing and proton-consuming reactions may be separated in time and space. The absence of mixing in untilled soils may lead to acidification of one soil layer with the alkalinisation of another layer. Indeed, untilled soils are frequently more acidic in the surface 7.5 cm and less acidic in deeper layers than ploughed soils (Table 11.6; Shear and Moschler, 1969; Moschler *et al.*, 1975; Blevins *et al.*, 1977; Mahler and Harder, 1984). Nitrification, which produces protons, is frequently slower in surface layers of untilled soils. However, when ammonium fertilisers are placed at the surface, greater amounts of protons may be produced in the surface layers than in deeper layers. The protons produced will be mixed throughout the soil on ploughing but retained in the surface layers in untilled soils. Additionally, effects of tillage on variation in soil pH with depth parallel effects on the distribution of both organic matter and extractable nutrients with depth (see above). Organic acids can be formed by microbial decomposition of plant residues, but any effects of addition of organic matter on soil pH will depend upon the initial pH and the degree of dissociation of the organic acids (Ritchie and Dolling, 1985). It is therefore difficult to ascertain whether the distribution of organic matter with depth is affecting the variation in soil pH with depth.

Table 11.6 The effect of tillage on soil pH (1/1:soil/water) after 6 years of continuous crop (Shear and Moschler, 1969)

Depth (cm)	Tilled	Untilled
0–5	4.8	4.5
5–10	5.0	4.6
10–15	5.2	5.2
15–20	5.3	6.0

Cereal cropping does not necessarily lead to soil acidification (Williams and Lipsett, 1961; Piper and de Vries, 1964), except where nitrogenous fertilisers are also applied. The nature and extent of effects of nitrogenous fertilisers on soil pH will depend on the form of nitrogen applied and the fate of the applied nitrogen (Table 11.7; Helyar, 1976). Hence, after the application of 20 kg nitrogen ha^{-1} to 14 soils, the mean annual decrease in soil pH was 0.02 units for urea and ammonium nitrate but 0.05 units for monoammonium phosphate and ammonium sulphate (Southern, 1981). In another study with continuous cropping the application of ammonium sulphate for 12 years at 76 kg nitrogen ha^{-1} yr^{-1} decreased the soil pH by 1 unit when compared with a treatment in which no nitrogen was applied (Mason, 1980). Urea application at the same rate decreased pH by only 0.2 to 0.6 of a unit depending on soil type.

Table 11.7 Effect of form of nitrogen applied and the fate of that nitrogen on the number of protons left in soil (Helyar, 1976)

Form	Fate	Result
NH_4^+	Plant uptake, removed in product	+1 proton
	Nitrified to nitrate before plant uptake	+1 proton
	Nitrified to nitrate, which is leached beyond root zone	+2 protons
NO_3^-	Plant uptake, removed in product	−1 proton
	Leached beyond root zone	No change
Nitrogen fixation	Removed in produce	No change
	Leached as nitrate	+1 proton

Soil acidification may occur under continuous pastures and under rotations with pasture phases (Donald and Williams, 1954; Williams and Donald, 1957; Williams, 1980; Bromfield *et al.*, 1983; Yeates *et al.*, 1984). In these studies there do not appear to be large differences among sites in the rate of soil acidification. In general the rate of acidification is such that at least 40-50 years are needed for soil pH to fall by 1 unit (for example Williams, 1980). In sites after long periods of pasture there may be marked variation in pH with depth.

Decreases in pH associated with clover growth are not confined to the surface 10 cm (Williams, 1980; Bromfield *et al.*, 1983). After 32 years of continuous subterranean clover pasture, soil pH was decreased to a depth of 30 cm; effects on the surface 3 cm were less than at deeper layers in the profile in both the pasture and virgin soils (Williams, 1980). In other studies examining undisturbed soils under old pastures on peaty sands, soil pH was also greater at the surface than in the deeper layers (Yeates *et al.*, 1984). Additionally, in Western Australia soil pH may be greater at the surface after pasture growth than in virgin sites (Table 11.8; Jarvis and Robson, 1983) but in deeper layers, soil pH was much lower in the pasture soil than in the virgin soil. Cultivation of these soils from under old pastures mixes these layers and may have marked effects on nodulation of legumes and growth of plants (Yeates *et al.*, 1984; Coventry *et al.*, 1985; Richardson *et al.*, 1985). Liming increased clover growth on cultivated sites but did not increase growth on undisturbed sites (Yeates *et al.*, 1984).

Table 11.8 Variation in soil pH and organic carbon with depth for a cultivated site and an adjacent virgin site (Jarvis and Robson, 1983); the cultivated site had been cleared for 26 years and, apart from five wheat crops, had been under subterranean clover pasture

Depth (cm)	pH (1/5 0.01 M $CaCl_2$)		Organic carbon (%)	
	Cultivated	Virgin	Cultivated	Virgin
0–3	5.33	4.89	0.93	0.39
3–7	4.58	4.62	0.90	0.26
7–12	4.27	4.49	0.63	0.33
12–18	4.12	4.49	0.23	0.23
> 18	4.33	4.55	0.11	0.10

CONCLUSIONS

There is clearly a need to examine the effect of tillage practices and residue management on chemical soil fertility for both continous cropping systems and legume ley rotations under Australian conditions. Many Australian studies have examined effects of tillage practices on yield without attempting to identify the mechanisms underlying yield responses. There have been very few studies in Australia in which effects of tillage on the components of chemical soil fertility have been assessed. Additionally, the gradual nature of such effects makes it imperative that the effect of tillage on chemical soil fertility be assessed for several years.

There are several areas of high priority for future research. Firstly, the effects of tillage and residue management on transformations of nitrogen in soil should be examined quantitatively. This is essential in order to predict the optimum rate of nitrogen application for particular situations. Secondly, there is a requirement to examine the effect of tillage and residue management on nutrient uptake in environments in which the surface soil is dry for long periods. Thirdly, the role of invertebrates in nutrient cycling needs to be examined. Finally, the effect of tillage during cropping on the subsequent establishment and production of pastures requires detailed investigation.

REFERENCES

Abbott, L.K. and Robson, A.D. (1982). The role of vesicular arbuscular mycorrhizal fungi in agriculture and the selection of fungi for inoculation. *Aust. J. Agric. Res.* 33:389.

Abbott, L.K. and Robson, A.D. (1984). The effect of VA mycorrhizae on plant growth. In 'VA Mycorrhiza', p.113. Edited by Powell, C.L. and Bagyaraj, D.J. (Press Inc: Boca Raton, Florida).

Amato, M., Jackson, R.B., Butler, J.H.A. and Ladd, J.N. (1984). Decomposition of plant material in Australian soils. II. Residual organic ^{14}C and ^{15}N from legume plant parts decomposing under field and laboratory conditions. *Aust. J. Soil Res.* **22**:331.

Anghinoni, I. and Barber, S.A. (1980). Predicting the most efficient phosphorus placement for corn. *Soil Sci. Soc. Am. J.* **44**:1016.

Anon. (1980). 'Atlas of Australian Resources'. Third Series Volume 1. Edited by Plumb, T. (Division of National Mapping: Canberra).

Bache, B.W. (1980). The acidification of soils. In 'Effects of Acid Precipitation on Terrestrial Ecosystems', p.183. Edited by Hutchinson, T.C. and Havas, M. (Plenum Press: New York).

Bacon, P.E. (1982). Interactions between carbon and nitrogen under intensive cropping sequences. In 'The Cycling of Carbon, Nitrogen, Sulfur and Phosphorus in Terrestrial and Aquatic Ecosystems', p.89. Edited by Galbally, I.C. and Freney, J.R. (Australian Academy of Science: Canberra).

Barley, K.P. and Jennings, A.C. (1959). Earthworms and soil fertility. III. The influence of earthworms on the availability of nitrogen. *Aust. J. Agric. Res.* **10**:364.

Biederbeck, V.O., Campbell, C.A. and Zentner, R.P. (1984). Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. *Can. J. Soil Sci.* **64**:355.

Biederbeck, V.O., Campbell, C.A., Bowren, K.E., Schnitzer, M. and McIver, R.N. (1980). Effect of burning cereal straw on soil properties and grain yields in Saskatchewan. *Soi Sci. Soc. Am. J.* **44**:103.

Black, R. and Tinker, P.B. (1979). The development of endomycorrhizal root systems. II. Effect of agronomic factors and soil conditions on the development of vesicular-arbuscular mycorrhizal infection in barley and on endophyte spore density. *New Phytol.* **83**:401.

Blevins, R.L., Thomas, G.W. and Cornelius, P.L. (1977). Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous cropping. *Agron. J.* **69**:383.

Brennan, R.F., Gartrell, J.W. and Robson, A.D. (1980). Reactions of copper with soil affecting its availability to plants. I. Effects of soil type and time. *Aust. J. Soil Res.* **18**:447.

Brennan, R.F., Gartrell, J.W. and Robson, A.D. (1984). Reactions of copper with soil affecting its availability to plants. III. Effect of incubation temperature. *Aust. J. Soil Res.* **22**:165.

Brennan, R.F., Gartrell, J.W. and Robson, A.D. (1985). The decline in the availability to plants of applied copper fertilizer. *Aust. J. Agric. Res.* **37**:107.

Brennan, R.F., Robson, A.D. and Gartrell, J.W. (1983). Reactions of copper with soil affecting its availability to plants. II. Effects of soil pH, soil sterilization and organic matter on the availability of applied copper. *Aust. J. Soil Res.* **21**:155.

Broder, M.W., Doran, J.W., Peterson, G.A. and Fenster, C.R. (1984). Fallow tillage influence on spring populations of soil nitrifiers, denitrifiers, and available nitrogen. *Soil Sci. Soc. Am. J.* **48**:1060.

Bromfield, S.M., Cumming, R.W., David, D.J. and Williams, C.H. (1983). Changes in soil pH, manganese and aluminium under subterranean clover pasture. *Aust. J. Exp. Agric. Anim. Husb.* **23**:181.

Burford, J.R. and Bremner, J.M. (1975). Relationships between the denitrification capacities of soil and total, water soluble and readily decomposable soil organic matter. *Soil Biol. Biochem.* 7:389.

Burford, J.R., Dowdell, R.J. and Crees, R. (1981). Emission of nitrous oxide to the atmosphere from direct-drilled and ploughed clay soils. *J. Sc. Fd. Agric.* **32**:219.

Cannell, R.Q. and Graham, J.P. (1979). Effects of direct drilling and reduced cultivation on the nutrient content of shoots of winter wheat and spring barley on clay soils during an unusually dry season. *J. Sc. Fd.Agric.* **30**:267.

Clarke, A.L. (1984). Crop rotations in dryland farming systems. *Proc. Intern. Cong. Dryland Farming* Adelaide, p.316.

Clarke, A.L. and Russell, J.S. (1977). Crop sequential practices. In 'Soil Factors in Crop Production in a Semi-Arid Environment', p.279. Edited by Russell, J.S. and Greacen, E.L. (Univ. Qld Press: St Lucia, Queensland).

Cooke, J.W., Ford, G.W., Dumsday, R.G. and Willatt, S.T. (1985). Effect of fallowing practices on the growth and yield of wheat in south-eastern Australia. *Aust. J. Exp. Agr.* **25**:614.

Coventry, D.R., Hirth, J.R., Reeves, T.G. and Jones, H.R. (1985). Changes in soil populations of *Rhizobium trifolii* following crop establishment in a clover-ley rotation in south-east Australia. *Proc. XV Int. Grassl. Cong.* (in press).

Crack, B.J. (1972). Changes in soil nitrogen following different establishment procedures for Townsville stylo on a solodic soil in north-eastern Queensland. *Aust. J. Exp. Agric. Anim. Husb.* **12**:274.

Craswell, E.T. (1978). Some factors influencing denitrification and immobilization in a clay soil. *Soil Biol. Biochem.* **10**:241.

Craswell, E.T. and Martin, A.E. (1975). Isotope studies of the nitrogen balance in a cracking clay. II. Recovery of nitrate ^{15}N added to columns of packed soil and microplots growing wheat in the field. *Aust. J. Soil Res.* **13**:53.

Dalal, R.C. and Strong, W.M. (1984). Microbial biomass turnover of soil and fertilizer nitrogen upon addition of crop residues to a black earth. *Proc. National Soils Congr.* Brisbane, p.378.

Davies, D.B. and Cannell, R.Q. (1975). Review of experiments on reduced cultivation and direct drilling in the United Kingdom, 1957-1974. *Outl. Agric.* **8**:216.

Donald, C.M. and Williams, C.H. (1954). Fertility and productivity of a podsolic soil as influenced by subterranean clover (*Trifolium subterraneum* L.) and superphosphate. *Aust. J. Agric. Res.* **5**:664.

Doran, J.W. (1980). Soil microbial and biochemical changes associated with reduced tillage. *Soil Sci. Soc. Amer. J.* **44**:765.

Doran, J.W. and Power, J.F. (1983). The effects of tillage on the nitrogen cycle in corn and wheat production. In 'Nutrient Cycling in Agricultural Ecosystems', p.441. Edited by Lowrance, R.R., Todd, R.L., Asmussen, L.E. and Leonard, R.A. (Univ. of Georgia College of Agric. Special Publication 23: Athens, Georgia).

Dowdell, R.J. and Cannell, R.Q. (1975). Effect of ploughing and direct drilling on soil nitrate content. *J. Soil Sci.* **26**:53.

Dowdell, R.J., Crees, R. and Cannell, R.Q. (1983). A field study of effects of contrasting methods of cultivation on soil nitrate content during autumn, winter and spring. *J. Soil Sci.* **34**:367.

Drew, M.C. and Saker, L.R. (1978). Effects of direct drilling and ploughing on root distribution in spring barley, and on the concentrations of extractable phosphate and potassium in the upper horizons of a clay soil. *J. Sc. Fd. Agric.* **29**:201.

Drew, M.C. and Saker, L.R. (1980). Direct drilling and ploughing: their effects on the distribution of extractable phosphorus and potassium and of roots in the upper horizons of two clay soils under winter wheat and spring barley. *J. Agric. Sci.* **94**:411.

Ehlers, W. (1975). Observations on earthworm channels and infiltration in tilled and untilled loess soil. *Soil Sci.* **119**:242.

Estes, G.O. (1972). Elemental composition of maize grown under no-till and conventional tillage. *Agron. J.* **64**:733.

Fenster, C.R. and Peterson, G.A. (1979). Effects of no-tillage fallow as compared to conventional tillage in a wheat-fallow system. *Neb. Agric. Exp. Stn. Res. Bull*: 289.

Firestone, M.K. (1982). Biological denitrification. In 'Nitrogen in Agricultural Soils', p.289. Edited by Stevenson, F.J. Agronomy Monograph 22. (American Society of Agronomy: Madison, USA).

Fleige, H. and Bauemer, K. (1974). Effect of zero-tillage on organic carbon and total nitrogen content, and their distributions in different N fractions in loessial soils. *Agro-Ecosystems* **1**:19.

French, R.J. (1978). The effect of fallowing on the yield of wheat. I. The effect on soil water storage and nitrate supply. *Aust. J. Agric. Res.* **29**:653.

Gartrell, J.W. (1981). Distribution and correction of copper deficiency in crops and pastures. In 'Copper in Soils and Plants', p.313. Edited by Loneragan, J.F., Robson, A.D. and Graham, R.D. (Academic Press: Sydney).

Gilkes, R.J. and Sadleir, S.B. (1979). The influence of placement geometry on the effectiveness of copper superphosphate. *Aust. J. Soil Res.* **17**:121.

Gilkes, R.J., Young, R.C. and Quirk, J.P. (1975). Leaching of copper and zinc from trace element superphosphate. *Aust. J. Soil Res.* **13**:33.

Greenland, D.J. (1971). Changes in the nitrogen status and physical conditions of soils under pastures with special reference to the maintenance of the fertility of Australian soils growing wheat. *Soils Fert.* **34**:237.

Groffman, P.M. (1984). Nitrification and denitrification in conventional and no-tillage soils. *Soil Sci. Soc. Am. J.* **49**:329.

Grundon, N.J. (1980). Effectiveness of soil dressings and foliar sprays of copper sulphate in correcting copper deficiency of wheat (*Triticum aestivum*) in Queensland. *Aust. J. Exp. Agric. Anim. Husb.* **20**:717.

Hall, I.R. (1980). Growth of *Lotus pedunculatus* Car. in an eroded soil containing soil pellets infested with endomycorrhizal fungi. *NZ J. Agric. Res.* **23**:103.

Hallsworth, E.G. (1969). The measurement of soil fertility: the National Soil Fertility project. *J. Aust. Inst. Agric. Sci.* **35**:78.

Hamblin, A.P. and Tennant, D. (1979). Interaction between soil type and tillage level in a dryland situation. *Aust. J. Soil Res.* **17**:177.

Hayman, D.S., Johnson, A.M. and Ruddlesdin, I. (1975). The influence of phosphate and crop species on *Endogone* spores and vesicular-arbuscular mycorrhiza under field conditions. *Plant Soil* **43**:489.

Helyar, K.R. (1976). Nitrogen cycling and soil acidification. *J. Aust. Inst. Agric. Sci.* **42**:217.

Hooker, M.L. and Schepers, J.S. (1984). Effect of residue removal vs incorporation on nitrogen uptake and growth of winter wheat. In 'Agronomy Abstracts', p.207. Annual Meeting, American Society of Agronomy, Crop Science Society of America and Soil Science Society of America. (American Society of Agronomy: Madison, USA).

Hooker, M.L., Herron, G.M. and Penas, P. (1982). Effects of residue burning, removal and incorporation on irrigated cereal crop yields and soil chemical properties. *Soil Sci. Soc. Am. J.* **46**:122.

Hutchinson, K.J. and King, K.L. (1982). Invertebrates and nutrient cycling. *Proc. 3rd Aust. Conf. Grassl. Inver. Ecol.*:331.

Jarvis, S.C. and Robson, A.D. (1983). The effect of nitrogen nutrition of plants on the development of acidity in Western Australian soils. I. Effects with subterranean clover grown under leaching conditions. *Aust. J. Agric. Res.* **34**:341.

Jarvis, R.J., Hamblin, A.P. and Delroy, N.D. (1985). Continuous cereal cropping with alternative tillage systems in Western Australia. West. Aust. Dept. Agric. Tech. Bull. p.71.

Jenkinson, D.S. (1977). Studies on the decomposition of plant materials in soil. *J. Soil Sci.* **28**:417.

Kohn, G.D., Storrier, R.R. and Cuthbertson, E.G. (1966). Fallowing and wheat production in southern New South Wales. *Aust. J. Exp. Agric. Anim. Husb.* **6**:233.

Kruckelmann, H.W. (1975). Effects of fertilizers, soils, soil tillage, and plant species on the frequency of *Endogone* chlamydospores and mycorrhizal infection in arable soils. In 'Endomycorrhizas', p.527. Edited by Sanders, F.E., Mosse, B. and Tinker, P.B. (Academic Press: London).

Ladd, J.N. and Russell, J.S. (1983). Soil nitrogen. In 'Soils: An Australian Viewpoint', p.589. Division of Soils, CSIRO (CSIRO: Melbourne/Academic Press: London).

Ladd, J.N., Oades, J.M. and Amato, M. (1981). Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. *Soil Biol. Biochem.* **13**:251.

Ladd, J.N., Amato, M., Jackson, R.B. and Butler, J.H.A. (1983a). Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. *Soil Biol. Biochem.* **15**:231.

Ladd, J.N., Jackson, R.B., Amato, M. and Butler, J.H.A. (1983b). Decomposition of plant material in Australian soils. I. The effect of quantity added on decomposition and on residual microbial biomass. *Aust. J. Soil Res.* **21**:563.

Lamb, J.A., Peterson, G.A. and Fenster, C.R. (1984). The effects of tillage systems on nitrogen mineralisation in a wheat-fallow rotation. In 'Agronomy Abstracts', p.210. Annual Meeting, American Society of Agronomy, Crop Science Society of America and Soil Science Society of America. (American Society of Agronomy: Madison, Wisconsin, USA).

Lamb, J.A., Peterson, G.A. and Fenster, C.R. (1985). Wheat fallow tillage systems' effect on newly cultivated grassland soils' nitrogen budget. *Soil Sci. Soc. Am. J.* **49**:352.

Littler, J.W. and Marley, J.M.T. (1978). Fallowing and winter cereal production on the Darling Downs - Progress Report 1968-78. Dept Primary Industries, Queensland.

Loch, R.J. and Coughlan, K.J. (1984). Effects of zero tillage and stubble retention on some properties of a cracking clay. *Aust. J. Soil Res.* **22**:91.

Loneragan, J.F., Snowball, K. and Robson, A.D. (1976). Remobilization of nutrients and its significance in plant nutrition. In 'Transport and Transfer Processes in Plants', p.463. Edited by Wardlaw, I.F. and Passioura, J.B. (Academic Press: Sydney).

Lynch, J.M. and Panting, L.M. (1979). Cultivation and the soil biomass. *Soil Biol. Biochem.* **12**:29.

Mahler, R.L. and Harder, R.W. (1984). The influence of tillage methods, cropping sequence, and N rates on the acidification of a northern Idaho soil. *Soil Sci.* **137**:52.

Mahler, R.L., Hammel, J.E. and Harder, R.W. (1985a). The influence of crop rotation and tillage methods on DTPA-extractable boron in northern Idaho soils. *Soil Sci.* **139**:67.

Mahler, R.L., Hammel, J.E. and Harder, R.W. (1985b). The influence of crop rotation and tillage methods on DTPA-extractable copper, iron, manganese and zinc in northern Idaho soils. *Soil Sci.* **139**:279.

Mason, M.G. (1980). An investigation of reduction in wheat yields after use of a high level of ammonium sulphate for a number of years. *Aust. J. Exp. Agric. Anim. Husb.* **20**:210.

McGarity, J.W. and Myers, R.J.K. (1968). Denitrifying activity in solidized solonetz soils of eastern Australia. *Soil Sci. Soc. Amer. Proc.* **32**:812.

Moschler, W.M., Martens, D.C. and Shear, G.M. (1975). Residual fertility in soil continuously field cropped to corn by conventional tillage and no-tillage methods. *Agron. J.* **67**:45.

Mosier, A.R., Melhuish, F.M. and Meyer, W.S. (1985). Direct measurement of denitrification using acetylene blockage and infrared gas analysis in a root zone lysimeter. In 'Root Zone Limitations to Crop Production on Clay Soils', p.101. Symposium of the Australian Society of Soil Science Incorporated, Riverina Branch. (CSIRO: Melbourne).

Mulligan, M.F., Smucker, A.J.M. and Safir, G.F. (1985). Tillage modifications of dry edible bean root colonization by VAM fungi. *Agron. J.* 77:140.

Ocampo, J.A. (1980). Effect of crop rotations involving host and non-host plants on vesicular-arbuscular mycorrhizal infection of host plants. *Plant Soil* **56**:283.

O'Toole, P., Morgan, M.A. and McGarry, S.J. (1985). A comparative study of urease activity in pasture and tillage soils. *Comm. Soil Sci. Pl. Anal.* **16**:759.

Parr, J.F. and Papendick, R.I. (1978). Factors affecting the decomposition of crop residues by microorganisms. In 'Crop Residue Management Systems', p.101. Edited by Oschwald, W.R. (Am. Soc. Agron: Madison, Wisc).

Piper, C.S. and de Vries, M.P.C. (1964). The residual value of superphosphate on a red brown earth in South Australia. *Aust. J. Agric. Res.* **15**:234.

Powell, C.L. (1982). Effects of kale and mustard crops on response of white clover to VA mycorrhizal inoculation in pot trials. *NZ J. Agric. Res.* **25**:461.

Reeves, T.G. and Ellington, A. (1974). Direct drilling experiments with wheat. *Aust. J. Exp. Agric. Anim. Husb.* **14**:237.

Reuter, D.J. (1975). The recognition and correction of trace element deficiencies. In 'Trace Elements in Soil-Plant-Animal Systems', p.291. Edited by Nicholas, D.J.D. and Egan, A.R. (Academic Press: New York).

Richardson, A.E., James, G.S. and Simpson, R.J. (1985). Enumeration and distribution of *Rhizobium trifolii* in an acid soil and implications for nodulation of subterranean clover. *Proc. 3rd Aust. Agron. Conf.* Hobart, p.51.

Ritchie, G.S.P. and Dolling, P.J. (1985). The role of organic matter in soil acidification. *Aust. J. Soil Res.* **23**:569.

Robson, A.D. (1984). The role of fertilizers in the development and maintenance of soil fertility in dry land farming systems. *Proc. Intern. Cong. Dryland Farming* Adelaide, p.472.

Robson, A.D., Loneragan, J.F., Gartrell, J.W. and Snowball, K. (1984). Diagnosis of copper deficiency in wheat by plant analysis. *Aust. J. Agric. Res.* **35**:347.

Rooney, D.R., Sims, H.J. and Tuohey, C.L. (1966). Cultivation trials in the Wimmera. *J. Dept Agric. Vic.* **64**:403.

Roper, M.M. (1983). Field measurements of nitrogenase activity in soils amended with wheat straw. *Aust. J. Agric. Res.* **34**:725.

Roper, M.M. (1985). Straw decomposition and nitrogenase activity (C_2H_2 reduction): effects of soil moisture and temperature. *Soil Biol. Biochem.* **17**:65.

Rowell, D.L. and Wild, A. (1985). Causes of soil acidification: a summary. *Soil Use and Management* **1**:32.

Rowell, D.L., Osborne, G.J., Matthews, P.G., Stonebridge, W.C. and McNeill, A.A. (1977). The effects in a long term trial of minimum and reduced cultivation on wheat yields. *Aust. J. Exp. Agric. Anim. Husb.* **17**:802.

Rowland, I.C., Halse, N.J. and Fitzpatrick, E.N. (1984). The role of legumes in dryland agriculture. *Proc. Intern. Cong. Dryland Farming* Adelaide, p.676.

Russell, J.S. (1975). A mathematical treatment of the effect of cropping system on soil organic nitrogen in two long term sequential experiments. *Soil Sci.* **120**:37.

Russell, J.S. (1981). Models of long term soil organic nitrogen change. In 'Simulation of Nitrogen Behaviour in Soil-Plant Systems', p.222. Edited by Fissell, M.J. and van Veen, J.H. (Pudoc: Wageningen).

Russell, J.S. and Williams, C.H. (1982). Biogeochemical interactions of carbon, nitrogen, sulfur and phosphorus in Australian agroecosystems. In 'The Cycling of Carbon, Nitrogen, Sulfur and Phosphorus in Terrestrial and Aquatic Ecosystems', p.61. Edited by Galbally, I.E. and Freney, J.R. (Australian Academy of Science: Canberra).

Saffigna, P.G., Powlson, D.S., Brookes, P.C., Standley, J., Thomas, G. and Hunter, H. (1984). Influence of tillage and sorghum residues on carbon, nitrogen and phosphorus in the soil microbial biomass of a vertisol in central Queensland. *Proc. National Soils Conf.* Brisbane, p.378.

Sequi, P., Cercignani, G., De Nobile, M. and Pagliai, M. (1985). A positive trend among two soil enzyme activities and a range of soil porosity under zero and conventional tillage. *Soil Biol. Biochem.* **17**:255.

Sharpley, A.N. and Syers, J.K. (1977). Seasonal variation in casting activity and in the amounts and release to solution of phosphorus forms in earthworm casts. *Soil Biol. Biochem.* **9**:227.

Shear, G.M. and Moschler, W.M. (1969). Continuous corn by the no-tillage and conventional tillage methods: a six year comparison. *Agron. J.* **61**:524.

Sieverding, E. and Leihner, D.E. (1984). Influence of crop rotation and intercropping of cassava with legumes on VA mycorrhizal symbiosis of cassava. *Plant Soil* **80**:143.

Smith, T.F. (1978a). Some effects of crop protection chemicals on the distribution and abundance of vesicular-arbuscular endomycorrhizas. *J. Aust. Inst. Agric. Sci.* **44**:82.

Smith, T.F. (1978b). A note on the effect of soil tillage on the frequency and vertical distribution of spores of vesicular-arbuscular endophytes. *Aust. J. Soil Res.* **16**:359.

Smith, T.F. (1980). The effect of season and crop rotation on the abundance of spores of vesicular-arbuscular (VA) mycorrhizal endophytes. *Plant Soil* **57**:457.

Sorenson, L.H. (1963). Studies on the decomposition of carbon-14 labelled barley straw in soil. *Soil Sci.* **95**:45.

Southern, P.J. (1981). Effects of fertilizers on soil pH in WA. *Our Land* **13**:6.

Spain, A.V., Isbell, R.F. and Probert, M.E. (1983). Soil organic matter. In 'Soils - an Australian Viewpoint', p.551. Division of Soils, CSIRO (CSIRO: Melbourne/Academic Press: London).

Stanford, G. and Smith, S.J. (1972). Nitrogen mineralization potentials of soils. *Soil Sci. Soc. Amer. Proc.* **36**:465.

Stanford, G. and Smith, S.J. (1976). Estimating potentially mineralizable soil nitrogen from a chemical index of soil nitrogen. *Soil Sci.* **122**:71.

Thomas, G.W., Blevins, R.L., Phillips, R.E. and McMahon, M.A. (1973). Nitrate nitrogen in killed corn cob. *Agron. J.* **65**:736.

Trappe, J.M., Molina, R. and Castellano, M. (1984). Reactions of mycorrhizal fungi and mycorrhizal formation to pesticides. *Ann. Rev. Phytopath.* **22**:331.

Triplett, G.B. and Van Doren, D.M. (1969). Nitrogen, phosphorus and potassium fertilization for non-tilled maize. *Agron. J.* **61**:637.

Tuohey, C.L. and Robson, A.D. (1980). The effect of cropping after medic and non-medic pastures on total soil nitrogen and on the grain yield and nitrogen contents of wheat. *Aust. J. Exp. Agric. Anim. Husb.* **20**:220.

Undersander, D.J. and Reiger, C. (1985). Effect of wheat residue management on continuous production of irrigated winter wheat. *Agron J.* 77:508.

Van Breeman, N., Mulder, J. and Driscoll, L.T. (1983). Acidification and alkalinisation of soils. *Plant Soil* **75**:283.

Williams, C.H. (1980). Soil acidification under clover pasture. *Aust. J. Exp. Agric. Anim. Husb.* **20**:561.

Williams, C.H. and Donald, C.M. (1957). Changes in organic matter and pH in a podzolic soil as influenced by subterranean clover and superphosphate. *Aust. J. Agric. Res.* **8**:179.

Williams, C.H. and Lipsett, J. (1961). Fertility in soils cultivated for wheat in southern New South Wales. *Aust. J. Agric. Res.* **12**:612.

Williams, C.H. and Simpson, J.R. (1965). Some effects of cultivation and waterlogging on the availability of phosphorus in pasture soils. *Aust. J. Agric. Res.* **16**:413.

Yeates, J.S., McGhie, D.A. and Wilson, I.R. (1984). Soil acidity. *J. Agric. W. Aust.* 25:138.