Decline in soil organic carbon and total nitrogen in relation to tillage, stubble management, and rotation

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Summary. The influence of rotation, tillage, stubble management, and nitrogen (N) fertiliser on soil organic carbon (C) and total nitrogen (N) was studied between 1979 and 1993 in a field experiment at Wagga Wagga, New South Wales, on a red earth. The rotations included lupin–wheat (LW), subterranean clover–wheat (SW), and continuous wheat (WW) with and without N fertiliser (100 kg N/ha).

At the start of the experiment the soil organic C and N in the surface 10 cm were high following many years of subterranean clover based pasture. The trends in soil organic C varied considerably between treatments from near equilibrium levels for SW direct-drilled and stubble-retained to annual losses of 400 kg/ha for WW conventionally cultivated and stubble burnt. Similarly, total soil N content over time varied from equilibrium levels to highly significant declines of 53 kg/ha.year for WW conventionally cultivated and stubble burnt. Both direct drilling and stubble retention reduced the losses of organic C and N compared with conventional cultivation and burning, with greatest loss occurring when cultivation and stubble burning were combined. SW and LW produced a similar contribution of fixed N to total N product removal, but greater benefits to following wheat crops were provided by SW rotations. Where losses of organic C and N were recorded there was no evidence of equilibrium levels being reached after 14 years.

Introduction

Sustainable agriculture depends largely on the conservation of soil organic carbon (C) to maintain soil chemical, physical, and biological fertility. In the undisturbed, virgin state, soil organic C levels are usually high because of little loss from vegetative or grain removal or erosion. With commercial agriculture a considerable amount of the dry matter produced is removed or burnt, erosion may occur, and cultivation may accelerate breakdown (e.g. Rasmussen and Collins 1991). The changes are relatively rapid at first, then slow as a new steady state is reached. Any new equilibrium will therefore depend on farming practices, particularly those affecting the inputs to and outputs from the system. Changes are often difficult to detect, considering the large background of soil organic matter and, so, need to be studied over the long term.

In the dryland wheat–sheep area of southern Australia, farmers have traditionally relied on legume-based pastures to maintain soil organic matter and soil nitrogen (N) (Greenland 1971). During the 1980s there was a deterioration in thrift of pasture legumes, combined with increased profitability of cropping (Dear *et al.* 1987; McCowan *et al.* 1987). This era also saw a marked increase in popularity of grain legumes, which, besides being cash crops, were also shown to contribute to the soil N supply for a following wheat crop (Evans *et al.* 1987; McCowan *et al.* 1987). The inclusion of grain legumes in the farm rotation, thereby at least partially replacing the ley system, has been promoted (Reeves *et al.* 1984; Delane *et al.* 1989; Mason and Rowland 1990). However, little information exists on the long-term effects of such rotations on soil organic C and N, particularly in relation to pasture–wheat rotations. Heenan and Chan (1992) found that the amount of soil N mineralised during the wheat phase was greater after subterranean clover pasture than after lupin.

Loss of organic C is generally assumed to be associated with a similar loss in organic N. However, Dalal and Mayer (1986) found that the C to N ratio in the surface 0.1 m can increase or decrease with time under cropping in either a linear or curvilinear manner, depending largely on soil type and, probably, initial fertility. Under pasture, the C to N ratio declined with time, even though both organic C and N increased (Watson 1969; Russell and Williams 1982).

In 1979, a field experiment was commenced at Wagga Wagga to investigate the stability of a range of rotation, tillage, and stubble management systems. Results have been presented on wheat production (Heenan *et al.* 1994), soil mineral N supply (Heenan and Chan 1992), and surface hydraulic properties (Chan and Heenan 1993). This paper reports results on the trends in soil organic C and N over 14 years.

Material and methods

Site

The field experiment is at the Agricultural Research Institute, Wagga Wagga (350°05'S, 1470°20'E), on a fertile red earth (Gn2.12, Northcote 1979), a chromic luvisol according to FAO-UNESCO classification. The site had been under a pasture of subterranean clover (*Trifolium subterraneum*), ryegrass (*Lolium* spp.), and barley grass (*Hordeum* spp.) for the previous 19 years except for crops of lupins (*Lupinus angustifolius*) and oats (*Avena sativa*) in 1975 and 1976, respectively. The surface 0.1 m was a clay loam with 29% clay, 15% silt, 1.3% organic (Walkley–Black) C, 0.13% total N, and pH(1 : 5 soil : 0.01 mol $CaCl_2$/L) 4.93 in 1979. The average annual rainfall was 550 mm.

Treatments

The 11 treatments are outlined in Table 1. The cultivars of wheat (*Triticum aestivum)* and lupin (*Lupinus angustifolius*) sown depended on current NSW Agriculture recommendations. The subterranean clover cultivar was Seaton Park until 1986, and a 1 : 1 mix of Seaton Park and Junee was used from 1987. Wheat and lupin were sown at 90 kg/ha, while subterranean clover was undersown with wheat at 5 kg/ha until 1987 and dropped onto wheat mulch at 10 kg/ha in the autumn of the clover phase throughout the experiment. Treatment 8 received 100 kg N/ha as urea in a 3-way split at sowing, mid-tillering, and flowering. All plots including subterranean clover received 20 kg phosphorus (P)/ha as single superphosphate at sowing. Recommended rates of rhizobia were applied with the legume seed for the first 3 years of the experiment only.

Plot size for most treatments was 4.3 by 50 m, except grazed subterranean clover, which was 60 by 50 m. The minimum grazing intensity during the growing season was 10 dry sheep equivalents (DSE)/ha. Treatment plots were separated by buffer plots measuring 4.3 by 50 m. Where stubble was retained, it was slashed between late December and early March. Burning of stubble occurred in autumn when fire control bans were lifted. Where stubble was retained in LW rotations, cultivation was done by offset disc harrows to 10 cm. A scarifier was used to a depth of 10 cm where stubble was burnt. The scarifier was also used in treatments 7, 8, and 9. Until 1987 all sowing was done by a 24-run conventional combine. For 1987 and thereafter, a direct-drilling undercarriage consisting of chisel points attached to narrow coil tines was employed.

Table 1. Details of treatments measured in this experiment

L, lupins; W, wheat; S, subterranean clover

Treatment no.	Rotation	Stubble management	Tillage
1	LW	Mulch	Direct drill
2	LW	Mulch	1 cultivation
3	LW	Mulch	3 cultivations
4	LW	Burn	Direct drill
5	LW	Burn	1 cultivation
6	LW	Burn	3 cultivations
7	WW	Burn	3 cultivations
8	WW(+N)	Burn	3 cultivations
9	S(grazed)W	Mulch	3 cultivations
10	S(mulched)W	Mulch	Direct drill
11	S(mulched)W	Mulch	3 cultivations

The experiment was laid out in 6 blocks, and treatments were arranged randomly within these blocks. Each phase of the lupin–wheat (LW) and subterranean clover–wheat (SW) rotation was represented each year in alternate blocks so that in any year each phase was replicated 3 times. For more information on treatments, management, and design see Heenan *et al.* (1994).

Measurements

At least 10 soil cores (5 or 2.5 cm diameter) per plot were taken to 10 cm depth before cultivation and sowing of the wheat phases of the various rotations in autumn. Composite core samples were bulked, dried in a forced draught oven at 40°C, and ground to pass through a 2-mm sieve. Organic C was analysed using the method of Walkley and Black (1934) adapted for colorimetric measurement (Sims and Haby 1971), and total N by Kjeldahl digestion. Organic C and total N are expressed on the same basis (t/ha, 0–10 cm) because the bulk density before cultivation varied with time from a mean of 1.54 g/cm^3 in 1979 to a mean of 1.33 g/cm^3 in 1993. The high value in 1979 was due to a long period of sheep trampling before the experiment. There was no significant difference between treatments in bulk density.

Statistical analyses

Repeated measurements were made on the same plots over the years. The year x treatment table of data was incomplete as data were not available for 1980, 1981, 1987, 1989, and 1991 for organic C, or 1980 and 1981 for total N. Also, some treatments were not measured in particular years; this affects 1982, 1984, and 1986.

A mixed model including both fixed and random effects was fitted to the data. Assuming normality of the errors and random effects, the fixed effects were estimated using the method of generalised least squares, and the random effect estimates were best linear unbiased predictors. The variance components were estimated using the method of residual maximum likelihood (Patterson and Thompson 1971).

The fixed terms included an intercept and slope for each treatment and a phase effect for treatments other than treatments 7 and 8. The random effects included a year effect to allow for year-to-year variation, a block effect to allow for serial correlation, and an year x treatment interaction effect.

Results and discussion

The effects of various treatments on wheat growth and yields were presented in Heenan *et al.* (1994). After 1982, responses were recorded to N fertiliser and a legume (subterranean clover or lupin) in the rotation and maintained for most of the experiment

Organic carbon

Organic C trends over 14 years varied considerably between treatments, from no significant change to annual losses of 0.4 t/ha (Table 2). The greatest rate of loss was when conventional (3 passes) cultivation was combined with stubble burning in an annual wheat-cropping system (Fig. 1*a*). The annual addition of 100 kg N/ha as fertiliser to wheat–wheat (WW), or changing to LW rotation, did not reduce the slope significantly when stubble burning and conventional cultivation were used. This was despite the presumably greater return of root material, considering the greater total aboveground dry matter production, from N fertilisation (Heenan *et al.* 1994). Ladd *et al.* (1994) also failed to find a significant response to N fertiliser where the stubble was burnt but did measure a response where the stubble was retained. Carter *et al.* (1993) reported that additions of 80 kg N/ha prevented organic C decline over 10 years of continuous wheat cropping where stubble was retained. These results suggest that the magnitude of any N response is related more to the amount of aboveground than root residue retained.

Within the LW rotation, retaining stubble appeared to reduce the rate of decline but the overall effect was not significant ($P<0.11$). This result seems to conflict with some studies (Mason 1992; Ladd *et al.* 1994) but is similar to others that found little or no effect of retaining stubble (Campbell *et al.* 1991; Carter and Mele 1992). A substantial effect of stubble retention is more likely when the initial organic C level is low (Campbell *et al.* 1991). In our study, the initial level was high following many years of subterranean clover based pasture, and significant rates of input from stubble are often difficult to detect against such a large background (Campbell *et al.* 1991; Rasmussen and Collins 1991). In addition, burning was done during early autumn following harvest in December, and some plant organic C may have been incorporated into the surface soil during summer via leaf fall and rainfall (Shields and Paul 1973; Cogle *et al.* 1987). Nevertheless, Chan *et al.* (1992), working on this experiment in 1989, did find significant effects of stubble retention on total C (dry combustion), biological activity, and aggregate stability in the surface soil. Because the soil C was measured by a methold different from that used in the present study, different fractions with different decay rates (Jenkinson and Rayner 1977) may be involved.

Estimates of the proportion of stubble C incorporated into the soil organic C pool can be made by calculating the amount of stubble returned over time and comparing this with the difference between stubble burnt and retained in soil organic C. We estimated that only 30% of lupin residue was successfully burnt in autumn, and all of the lupin leaves had fallen around physiological maturity in the previous spring. Therefore, 70% of lupin stubble would have been retained in the burnt stubble treatments. However, burning of wheat straw in autumn was invariably complete. Assuming a C concentration of 40% in crop stubbles, mean estimates of stubble C retained compared with burnt from 1979 to 1992 were 22.1 t C/ha for wheat stubble and 5.2 t C/ha for lupin stubble. Based on the difference in soil organic C of 1.26 t C/ha between stubble burnt and retained in early 1993, 4.6% of crop stubble C was incorporated into the soil organic C pool. This estimate compares with 16, 7, and 3% of cereal stubble C retained over 5, 13, and 20 years, respectively, of cropping in southern

Table 2. Slope, standard error, and *t*-value for fitted lines of soil organic carbon and total soil nitrogen over time

Treatment no.	Slope (kg C/ha.year)	Standard error	*t*-value	Slope (kg N/ha.year)	Standard error	*t*-value
1	–44	84	–0.52 n.s.	–12	13	–1.03 n.s.
2	–60	90	–0.66 n.s.	–8	13	–0.60 n.s.
3	–179	86	–2.09*	–27	14	–1.97*
4	–115	86	–1.35 n.s.	–27	13	–2.03*
5	–183	89	–2.05*	–27	14	–2.01*
6	–250	90	–2.79**	–44	13	–3.26**
7	–400	76	–5.29***	–53	13	–4.00***
8	–348	77	–4.50***	–47	13	–3.51***
9	–61	90	–0.68 n.s.	–0.5	14	–0.48 n.s.
10	–7	86	–0.08 n.s.	3	13	0.23 n.s.
11	–47	87	–0.54 n.s.	–11	13	–0.79 n.s.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$; n.s., not significant.

Queensland (Dalal *et al.* 1991), and 4% of wheat stubble retained over 7 years in north-eastern Victoria (Haines and Uren 1990). Sources of variation could include initial organic C level (Campbell *et al.* 1991), soil type and especially clay content (Saffigna *et al.* 1989), period of stubble retention (Dalal *et al.* 1991), efficiency of burning (Rasmussen and Collins 1991), and loss of stubble C to the soil between harvest and burning (Amato *et al.* 1987).

Conventional cultivation increased ($P<0.06$) the rate of loss of soil organic C compared with direct drilling. Similar findings have been reported for most studies (Russell and Williams 1982; Rasmussen and Collins 1991; Smettem *et al.* 1992) but not all (Haines and Uren 1990; Dalal *et al.* 1991). The loss of C with cultivation has been associated with reduced biological activity and soil structure (Chan *et al.* 1992; Chan *et al.* 1994). However, the maximum loss rate in the LW rotation occurred when stubble was burnt and soil conventionally cultivated, suggesting that the effects of these treatments were independent and additive. The greater loss of organic C with cultivation has been attributed to increased decomposition rate (Doran 1980; Blevins *et al.* 1983), erosion losses (Packer *et al.* 1984; Rasmussen and Collins 1991), or a redistribution of organic C within the soil profile (Doran 1980; Chan *et al.* 1992).

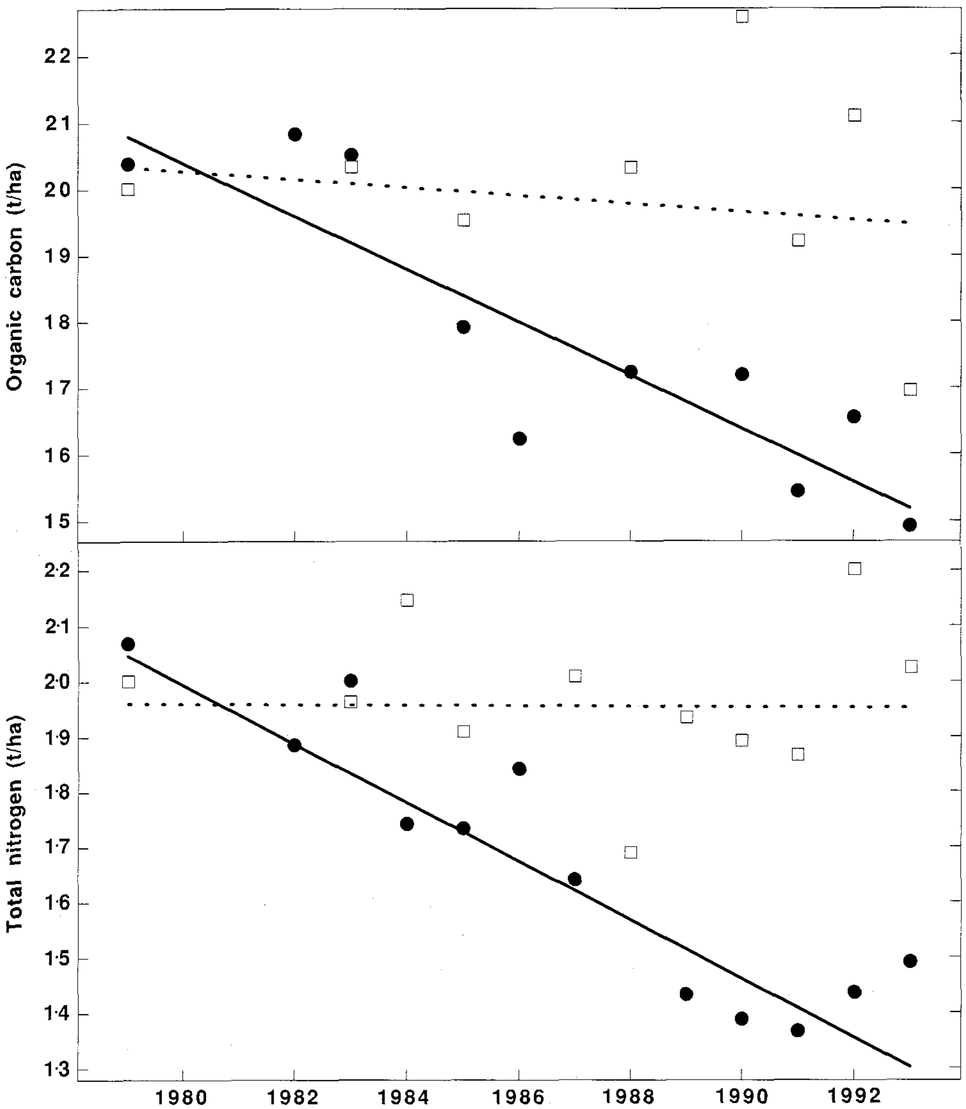

Figure 1. (*a*) Soil organic carbon and (*b*) total nitrogen content for treatments 7 (●) and 9 (□) from 1979 to 1992. The dashed and solid lines represent the fitted models.

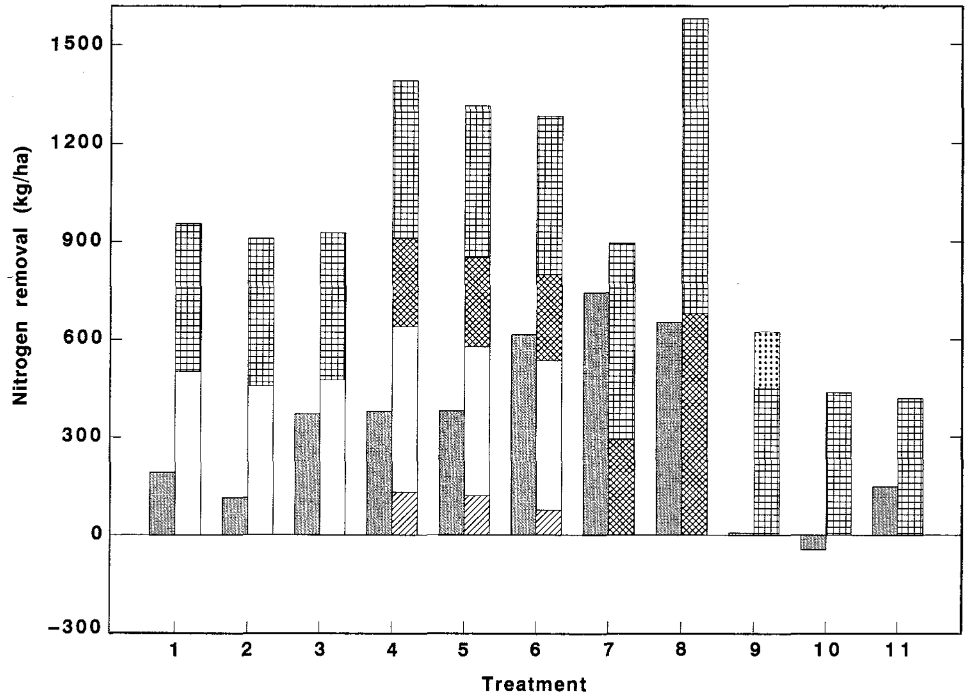

Figure 2. Total soil nitrogen removal (solid bars) and total N removal caused by lupin grain (open bars), wheat grain (cross-hatched bars), lupin stubble (striped bars), wheat stubble (diagonal cross-hatched bars), and sheep (stippled bars) over 15 years.

Total nitrogen

Most of the management effects on soil N were similar to those on soil C. The overall trends ranged from near equilibrium levels to a highly significant loss of 53 kg/ha.year for treatment 7 (Table 2, Fig. 1*b*).

For the same tillage and stubble treatments, SW rotations generally showed lower losses than LW rotations. Heenan and Chan (1992) found greater amounts of N mineralised during the wheat phase after subterranean clover (grazed) than after lupin. The removal of a large proportion of the fixed N in lupin grain was considered to be a major reason for the difference in N supply. Within SW rotations there was no significant change over time for the direct-drilled–mown and cultivated–grazed treatments, indicating that these systems were able to maintain a high level of soil N.

Within LW rotations the loss of N was reduced (P = 0.07) by retaining rather than burning stubble. As noted above, the positive effect of stubble retention compared with burning was most likely more related to retention of wheat than lupin stubble, due to the limited burn of the latter. Besides returning N in the wheat straw, retaining wheat stubble may have increased N_2 fixation and subsequent soil N benefits by the lupin (O'Connor *et al.* 1991).

As with organic C, conventional cultivation with stubble either burnt or retained in LW rotation increased the annual rate of decline of soil N by a mean of 15 kg N/ha. If cultivation increased mineralisation of soil organic N in the short term as proposed by Dowdell and Cannell (1975), over the long term the supply of organic N might diminish compared with direct drilling. The effects of cultivation were greater as the number of passes was increased from 1 to 3, and also where stubble was burnt.

Between 1979 and 1993 there was no net loss of soil N in the 10–20 cm layer from an initial level of 0.06%. By relating soil N lost in the surface 10 cm to N removal by the crops and sheep (assume 23 kg N/ha.year for 10 DSE/ha) from 1979 to 1993, we can make some estimates of the N budgets (Fig. 2).

The soil N loss estimates accounted for 88% of wheat removal on treatment 7, which did not receive additional N from legume N_2 fixation or N fertiliser. The additional N removed by the crop was possibly related to input from extraneous sources such as rainfall and non-symbiotic N_2 fixation (Vallis 1990). The annual addition of 100 kg N/ha resulted in an increased crop uptake at maturity of 696 kg N/ha over 14 years, with N fertiliser uptake efficiency of 50%. This value suggests considerable losses of fertiliser N. While the total nature of the loss mechanism(s) is not known, leaching losses of mineral N from the surface layers of this well-drained soil were highly likely (Heenan and Chan 1992) and could account for the high acidification of this treatment (Heenan and Taylor 1995).

With the treatment 3 LW rotation, the difference between total crop (wheat and lupin grain) N removal (937 kg N/ha) and soil N removal (378 kg N/ha) was 559 kg N/ha, which is an estimate of the contribution of fixed N to product removed from the system over the 14 years. Similarly, for treatment 9 SW rotations, the total N removal (wheat grain and sheep) was 623 kg N/ha and the contribution of fixed N to product removal over the 14 years was 616 kg N/ha. A major difference between the 2 rotations related to differences in N removal in the legume phase. Removal in lupin grain accounted for 476 kg N/ha, while sheep only removed 161 kg N/ha. Therefore, the overall contribution of legume-fixed or spared N to wheat grain N removal was 454 kg N/ha for SW and only 83 kg N/ha for LW. In this experiment, SW was only cultivated before the wheat phase while treatment 3 LW was cultivated before each crop. The greater number of cultivations over time in LW than in SW therefore may also have contributed to the disparity between the 2 treatments. When LW was direct-drilled with stubble retained (treatment 1), the contribution of legume-fixed or spared N to wheat grain N removal was 283 kg N/ha.

Though cultivation promoted soil N loss in LW and SW, the increased losses were not accounted for by increased crop removal. This suggests that other loss mechanisms, such as volatilisation, denitrification, and leaching, were also involved (Bacon and Osborne 1987).

The fixed N contribution to product removal was greater in grazed (615 kg N/ha) than mulched (272 kg N/ha) subterranean clover rotation (treatment 9 *v.* 11). While part of the difference related to product removal by sheep in treatment 9, grazing also supplied more N to the wheat crop (454 *v.* 272 kg N/ha). Possible explanations for differences between grazed and ungrazed subterranean clover are related to differences in botanical composition and especially legume density (Heenan *et al.* 1994), allelopathic effects from pasture residues on early growth and nodulation of legumes (Halsall *et al.* 1995), stimulation of N_2 fixation rate under grazing from less shading, or different losses of legume N via mechanisms such as volatilisation, leaching, or denitrification.

Carbon to nitrogen ratio

There was no significant change from the initial mean C to N ratio of 10 from 1979 to 1993 for any treatment. There was also no significant difference between the various treatments.

Conclusion

The results of this experiment demonstrate considerable variation between management treatments in degradation of organic C and total N over 14 years. Farming practices involving direct drilling and stubble retention were more able to maintain soil organic C and N than those employing traditional cultivation and stubble burning. Cultivation with 3 passes was similar to burning stubble in reducing soil organic C and N, and the processes were additive. Subterranean clover pasture, particularly when grazed or mulched, and wheat direct-drilled was able to maintain a high soil N level. However, rotations with lupin, particularly with stubble burnt and cultivated, reduced soil N. All C and N losses incurred were linear with no indication of an equilibrium being reached.

Acknowledgments

Many people have contributed to this experiment since 1979. In particular we thank Messrs P. Macrae, W. Littlewood, G. Poile, R. Sewell, P. Lockley, J. Carter, M. Stout and G. Heath for their valuable field assistance; A. Taylor and W. Lill for initial design and management; P. Olson for chemical analyses; and Dr B. Cullis for advice on statistical analysis. The experiment was funded in part by the Wheat Research Council and the Grains Research and Development Corporation.

References

Amato, M., Ladd, J. N., Ellington, A., Ford, G., Mahoney, J. E., Taylor, A. C., and Walsgott, D. (1987). Decomposition of plant material in Australian soils. IV. Decomposition *in situ* of ^{14}C- and ^{15}N-labelled legume and wheat materials in a range of southern Australian soils. *Australian Journal of Soil Research* **25**, 95–105.

Bacon, P. E., and Osborne, G. J. (1987). Effect of tillage and residue on the N cycle. *In* 'Nitrogen Cycling in Temperate Agricultural Systems'. (Eds P. E. Bacon, J. Evans, R. R. Storrier and A. C. Taylor.) pp. 360–79. (Australian Society of Soil Science Inc., Riverina Branch: Griffith, NSW.)

Blevins, R. L., Thomas, G. W., Smith, M. S., Frye, W. W., and Cornelius, P. L. (1983). Changes in soil properties after 10 years continuous non-tilled and conventionally tilled corn. *Soil and Tillage Research* **3**, 135–46.

Campbell, C. A., Bowren, K. E., Scnitzer, M., Zentner, R. P., and Townley-Smith, L. (1991). Effect of crop rotations and fertilization on soil organic matter and some biochemical properties of a black Chernozem. *Canadian Journal of Soil Science* **71**, 377–87.

Carter, H. R., and Mele, P. M. (1992). Changes in microbial biomass and structural stability at the surface of a duplex soil under direct drilling and stubble retention in north-eastern Victoria. *Australian Journal of Soil Research* **30**, 493–503.

Carter, M. R., Parton, W. J., Rowland, I. C., Schultz, J. E., and Steed, G. R. (1993). Simulation of soil organic carbon in cereal and pasture systems of southern Australia. *Australian Journal of Soil Research* **31**, 481–91.

Chan, K. Y., and Heenan, D. P. (1993). Surface hydraulic properties of a red earth under continuous cropping with different management practices. *Australian Journal of Soil Research* **31**, 13–24.

Chan, K. Y., Heenan, D. P., and Ashley, R. (1994). Seasonal changes in surface aggregate stability under different tillage and crops. *Soil and Tillage Research* **28**, 301–14.

Chan, K. Y., Roberts, W. P., and Heenan, D. P. (1992). Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices. *Australian Journal of Soil Research* **30**, 71–83.

Cogle, A. C., Saffigna, P. G., Strong, W. M., Ladd, J. N., and Amato, M. (1987). Wheat straw decomposition in subtropical Australia. 1. A comparision of ^{14}C labelling and two weight-loss methods for measuring decomposition. *Australian Journal of Soil Research* **25**, 473–9.

Dalal, R. C, Henderson, P. A., and Glasby, J. M. (1991). Organic matter and microbial biomass in a vertisol after 20 years of zero-tillage. *Soil Biology and Biochemistry* **23**, 435–41.

Dalal, R. C., and Mayer, R. J. (1986). Long term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. *Australian Journal of Soil Research* **24**, 281–92.

Dear, B. S., Cregan, P. D., and Hochman, Z. (1987). Factors restricting the growth of subterranean clover in N.S.W. and their implications for further research. *In* 'Temperate Pastures, their Production, Use and Management'. (Eds J. L. Wheeler, C. J. Pearson and G. E. Robards.) pp. 55–7. (AWC/CSIRO: East Melbourne.)

Delane, R. J., Nelson, P., and French, R. J. (1989). Roles of grain legumes in sustainable dryland cropping systems. *In* 'Proceedings of the 5th Australian Agronomy Conference, September 1989, Perth, Western Australia'. (Ed. G. P. Ayling.) pp. 181–96. (Australian Society of Agronomy: Parkville, Victoria.)

Doran, J. W. (1980). Soil microbial and biochemical changes associated with reduced tillage. *Soil Science Society of America Journal* **44**, 765–71.

Dowdell, R. J., and Cannell, R. Q. (1975). Effects of ploughing and direct drilling on soil nitrate concentration. *Journal of Soil Science* **26**, 53–61.

Evans, J., O'Connor, G. E., Turner, G. L., and Bergensen, F. J. (1987). Nitrogen fixation and accretion of soil nitrogen by soil grown lupins (*Lupinus angustifolius*). *Fields Crops Research* **16**, 791–805.

Greenland, D. J. (1971). Changes in the nitrogen status and physical condition of soils under pastures, with special reference to the maintenance of fertility of Australian soils. *Soils and Fertiliser* **34**, 237–51.

Haines P. J., and Uren, N. C. (1990) Effects of conservation tillage farming on soil microbial biomass, organic matter and earthworm populations, in north-eastern Victoria. *Australian Journal of Experimental Agriculture* **30**, 365–71.

Halsall, D. M., Leigh, J. H., Gollasch, S. E., and Holgate, M. (1995). The role of allelopathy in legume decline in pastures. II. Comparative effects of pasture, crop and weed residues on germination, nodulation and root growth. *Australian Journal of Agricultural Research* **46**, 189–207.

Heenan, D. P., and Chan, K. Y. (1992). The long term effects of rotation, tillage and stubble management on soil mineral supply to wheat. *Australian Journal of Soil Research* **30**, 977–88.

Heenan, D. P., and Taylor, A. C. (1995). Soil pH decline in relation to rotation, tillage, stubble retention and nitrogen fertiliser in south-eastern Australia. *Soil Use Management* **11**, 4–9.

Heenan, D. P., Taylor, A. C., Cullis, B. R., and Lill, W. J. (1994). Long term effects of rotation, tillage and stubble management on wheat production in southern N.S.W. *Australian Journal Agricultural Research* **45**, 93–117.

Jenkinson, D. S., and Rayner, J. H. (1977). The turnover of soil organic matter in some Rothamsted classical experiments. *Soil Science* **123**, 298–305.

Ladd, J. N., Amato, M., Zhou, Li-Kai, and Schultz, J. E. (1994). Differential effects of rotation, plant residue and nitrogen fertiliser on microbial biomass and organic matter in an Australian alfisol. *Soil Biology and Biochemistry* **26**, 821–31.

Mason, M. G. (1992). Effect of management of previous cereal stubble on nitrogen fertiliser requirement of wheat. *Australian Journal of Experimental Agriculture* **32**, 355–62

Mason, M. G., and Rowland, I. C. (1990). Nitrogen fertiliser response of wheat in lupin–wheat, subterranean clover–wheat and continuous wheat rotations. *Australian Journal of Experimental Agriculture* **30**, 231–6.

McCowan, R. L., Cogle, A. L., Ockwell, A. P., and Reeves, T. G. (1987). Nitrogen supply to cereals in legume ley systems under pressure. *In* 'Symposium on Advances in Nitrogen Cycling in Agricultural Systems, Brisbane, May 1987'. (Ed. J. R. Wilson.) pp. 292–314. (CAB International: Wallingford, UK.)

Northcote, K. H. (1979). 'A Factual Key for Recognition of Australian Soils.' 4th Edn. (Rellim Technical Publications: Glenside, S. Aust.)

O'Connor, G. E., Evans, J., Fettell, N., Bamforth, L., Stuchbery, J., Heenan, D., and Chalk, P. M. (1991). Managing field pea for maximum N_2 fixation. *In* 'Proceedings of the 9th Australian Nitrogen Fixation Conference, January 1991, Canberra, A.C.T'. (Eds A. E. Richardson and M. B. Peoples.) p. 143. (The Australian Society for Nitrogen Fixation: Canberra.)

Packer, I. J., Hamilton, G. J., and White, I. (1984). Tillage practices to conserve soil and improve soil conditions. *Soil Conservation Journal of N.S.W.* **40**, 78–87.

Patterson, H. D., and Thompson, R. (1971). Recovery of interblock information when block sizes are unequal. *Biometrika* **58**, 545–54.

Rasmussen, P. E., and Collins, C. H. (1991). Long-term impacts of tillage, fertiliser, and crop residue on soil organic matter in temperate semiarid regions. *Advances in Agronomy* **45**, 93–134.

Russell, J. S., and Williams, C. H. (1982). Biochemical interactions between nitrogen, sulfur and phosphorus in Australian agroecosystems. *In* 'The Cycling of Carbon, Nitrogen, Sulfur and Phosphorus in terrestrial and Aquatic Ecosystems'. (Eds I. E. Galbally and J. F. Freney.) pp. 61–75. (Springer-Verlag: New York.)

Reeves, T. G., Ellington, A., and Brooke, H. D. (1984). Effects of lupin wheat rotations on soil fertility, crop disease and crop yield. *Australian Journal of Experimental Agriculture and Animal Husbandry* **24**, 595–600.

Saffigna, P. G., Powlson, D. S., Brookes, P. C., and Thomas, G. A. (1989). Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an Australian vertisol. *Soil Biology & Biochemistry* **21**, 759–65.

Shields, J. A., and Paul, E. A. (1973). Decomposition of ^{14}C plant material under field conditions. *Canadian Journal of Soil Science*. **53**, 297–306.

Sims, J. R., and Haby, V. A. (1971). Simplified colorimetric determination of soil organic matter. *Soil Science* **112**, 137–41.

Smettem, K. R. J., Rovira, A. D., Wace, S. A., Wilson, B. R., and Simon, A. (1992). Effect of tillage and crop rotation on surface stability and chemical properties of a red-brown earth (Alfisol) under wheat. *Soil and Tillage Research* **22**, 27–40.

Vallis, I. (1990). Nitrogen: the most limiting element in agriculture. *Journal of the Australian Institute of Agricultural Science* **3**, 19–23.

Walkley, A., and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38.

Watson, E. R. (1969). The influence of subterranean clover pastures on soil fertility. III. The effect of applied phosphorus and sulphur. *Australian Journal of Agricultural Research* **20**, 447–56.

Received 5 January 1995, accepted 13 July 1995