ORGANIC CARBON IN FORESTED SANDY SOILS: PROPERTIES, PROCESSES, AND THE IMPACT OF FOREST MANAGEMENT

J. C. CARLYLE

Division of Forestry, CSIRO, Plantation Forest Research Centre,
Mount Gambier, S.A. 5290, Australia.

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ABSTRACT

Data from a series of experiments illustrated the importance of organic carbon in influencing a range of key determinants of plantation productivity on podsolised sands, which lack a significant inorganic colloidal phase. Organic carbon levels affected soil nitrogen reserves, nitrogen dynamics, phosphorus availability, and cation exchange capacity.

Evidence from two experiments indicated that the organic carbon in podsolised sands is highly dynamic and sensitive to management operations which influence organic carbon inputs, decomposition rates, or both. Weeds can help maintain organic carbon reserves after clearfelling, particularly where logging residues have been burnt. Retention of above-ground logging residues also helps to maintain organic carbon reserves. Most harvesting and site preparation operations result in loss of a labile carbon pool (representing approximately 30% of total carbon). This pool can be buffered by residue retention and weeds in the period before significant litter inputs from the new crop, but in any case will be replenished once these inputs are resumed. As such, the impact of management on this pool is likely to be transient. Long-term reductions in soil carbon and associated properties are likely only where management operations result in loss from the recalcitrant carbon pool (representing approximately 70% of total carbon). Since such material decomposes extremely slowly, only site preparation operations such as surface soil scalping or the use of high-intensity fire are likely to result in significant short-term losses of this fraction.

Keywords: organic carbon; podsolised sands; weed management; residue management; soil nitrogen; soil phosphorus; nitrogen mineralisation; *Pinus radiata.*

INTRODUCTION

Approximately 30% of Australian softwood plantation production is dependent on soils with a sandy A horizon (sand and/or sandy loam) of aeolian or coastal origin. In south-east South Australia virtually all plantings of *Pinus radiata* D.Don (125 000 ha) have been established on podsolised sands, while extensive areas of subtropical and tropical pines (*P. elliottii* Engelm. and *P. caribaea* Morelet var. *hondurensis)* are grown in south Queensland on similar soils. Large areas of softwood plantations in Western Australia are also grown on podsolised sands. In general these sandy soils fall into one of two groups: (i) soils with a deep (>2 m) sandy A horizon, frequently exhibiting podsolic features such as an albic A2 horizon; and (ii) soils with a shallow sandy A horizon, often with an albic A2 horizon, which typically overlie a clay B horizon giving a duplex profile—these soils may exhibit humic or lateritic features.

The general influence of carbon on soil chemical and physical properties is well known. Its particular importance in sandy soils, which lack an inorganic colloidal phase, has been speculated upon (Flinn *et al.* 1980) and stressed (Gholz *et al.* 1985; Sands 1982). However, the extent to which carbon influences a wide range of key nutrient-supplying processes in sandy soils is less fully appreciated. Sandy soils are typified by low concentrations of organic carbon (hereafter referred to as carbon) and plant nutrients (Table 1). Carbon concentrations decline sharply with depth (Fig. 1) so that the surface soil (0–0.15 m) is the principal reservoir of carbon and organically bound elements (Stephens *et al.* 1941; Nambiar & Bowen 1986; Smethurst & Nambiar 1990a). In these soils the distribution of carbon and organically bound nutrients is closely paralleled by that of fine roots, with 90% of the fine root biomass of *P. radiata* occurring in the surface 0.30 m (Nambiar 1983). Consequently, surface soil properties, particularly those which affect nutrient-supplying processes, can have a major influence on plantation growth.

The quantity of carbon and nitrogen contained in slash and litter after harvesting of sandy soil sites can represent a substantial percentage of the total ecosystem capital, e.g., 10–37%

TABLE 1–Mean, standard errors (s.e.), and minimum and maximum values for selected soil properties (0–0.15 m, <2 mm) from the ROMP study (Carlyle *et al.* 1990; J.R.Lowther unpubl. data).

	Mean	s.e.	Minimum	Maximum
Organic C (mg/g)	12.3	1.3	3.9	45.7
Total N (mg/g)	0.55	0.06	0.20	2.00
Total P (µg/g)	39.3	3.1	14.0	95.0
Mineralisable N (µg/g)*	18.0	1.2	8.3	46.2
CEC (m mol[$\mathrm{Ca}^{+(1/2)}$]/kg)	37.9	3.4	11.6	114.9

* Nitrogen mineralised after 56 days' aerobic incubation at 20°C

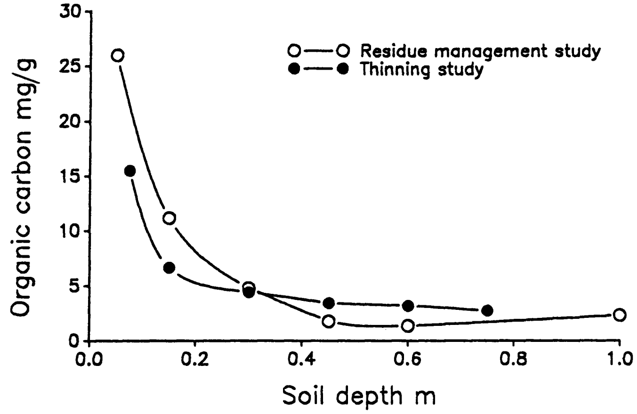

FIG. 1–Typical distribution of organic carbon concentrations (<2 mm) with depth in podsolised sands.

of system nitrogen and 56% of system carbon (Morris *et al.* 1983; Smethurst & Nambiar 1990b). Therefore, sandy soils are particularly sensitive to management practices which result in significant losses of carbon and nitrogen (Flinn *et al.* 1980; Burger & Pritchett 1988; Smethurst & Nambiar 1990b). In south-east South Australia there has been evidence of productivity decline between successive rotations of softwood plantations where windrowing and burning have resulted in loss of carbon and nitrogen contained in slash, litter, and surface soil (Keeves 1966). Concern has been expressed that similar site preparation practices in the *P. elliottii* forests growing on sandy podsols in the south-eastern United States may also lead to long-term decline in productivity (Burger & Pritchett 1988).

Because of the significance of sandy soils to Australian softwood plantation production and the sensitivity of these soils to management, CSIRO Division of Forestry, in collaboration with public and private forest owners, is conducting long-term studies which focus on the dynamics of carbon and nitrogen between crop rotations of *P. radiata* on sandy soils. In this paper I have drawn on data from several experiments to illustrate (i) the importance of carbon in influencing nitrogen and phosphorus concentrations and cation exchange capacity (CEC) in sandy soils, (ii) the dynamic nature of this carbon, and (iii) the impact of silvicultural operations on soil carbon concentrations.

DESCRIPTION OF FIELD EXPERIMENTS

All study sites were located on podsolised sandy soils in south-east South Australia/south-west Victoria. The region experiences a Mediterranean climate with cool wet winters and warm dry summers. For instance, mean monthly air temperatures at Mount Gambier (lat. 37°49′, long. 140°46′) range from a minimum of 10.8°C to a maximum of 25.2°C in January (mid-summer) and from a minimum of 5.4°C to a maximum of 13.7°C in June (mid-winter). Mean annual rainfall is 712 mm, 63% of which falls in winter and spring.

The information presented in this paper is drawn from four major studies.

1. Relationship between Chemical Properties and Nitrogen Mineralisation (ROMP)

This study, described in detail by Carlyle *et al.* (1990), examined the relationship between a range of chemical properties and nitrogen mineralisation in 39 sandy soils from south-east South Australia. Sites chosen for the study were representative of major *P. radiata*-growing areas in the region, soils being selected from plantations of different age and silvicultural history to provide a range of organic matter concentrations. All sites supported a pine crop varying in age from <1 to 13 years. At each site, 40 cores were taken at random from the mineral soil (excluding surface litter accumulations) to a depth of 0.15 m using a 25-mm-internal-diameter stainless steel tube. For each site, soil samples were bulked, homogenised, and air-dried at ambient temperature for 3 days. Dry soils were sieved (<2 mm) in a sealed container to prevent loss of fine organic material. All analyses were performed on the <2-mm fraction.

2. Weed Management

This experiment has been described in detail by Woods *et al.* (1992). The objectives of this study were to (i) examine the relationship between the degree of control of annual weeds and tree water and nitrogen status, and (ii) determine the nature and degree of competition for nitrogen between trees and weeds. The site previously supported a 17-year-old *P. radiata* plantation which was destroyed by a wild fire in 1983. After the fire, standing dead timber was felled, raked into windrows, and burnt. These events would have caused large losses of carbon and nitrogen from the site (Smethurst & Nambiar 1990a). The site was planted in 1985 at a spacing of 3 × 2.5 m, weeds were chemically controlled to give a 1-m weed-free strip which spanned the tree row. In 1987, weed control treatments were imposed on the site to obtain weed-free strips of different widths spanning the tree rows. These treatments provided the opportunity to quantify the effect of weeds and weed removal on soil carbon and nitrogen dynamics by providing areas which had supported weeds since site preparation, i.e., prior to 1985 (Weedy), areas where weeds were chemically controlled since 1985 (Weed Free), and areas where weeds were chemically controlled in May 1987 (Weed Kill). The Weed Kill and Weedy areas had identical management histories until the former received chemical weed control in May 1987. Soil (0–0.15 m) was collected at approximately 8-weekly intervals using 50-mm-internal-diameter PVC tubes. At each sampling, 16 cores were taken per replicate and bulked to give one composite sample. There were four replicates per treatment. Soil was not sieved prior to analysis.

3. Residue Management

This experiment has been described in detail by Smethurst & Nambiar (1990 a, b). The objective of the study was to examine the effects of clearfelling and residue management on site nitrogen and carbon dynamics. The 37-year-old plantation was felled in August 1984 and treatments were established within 4 months of felling. Four residue-manipulation treatments were imposed on a clearfelled site: residue and litter retained; litter only retained; litter only retained and ploughed; residue and litter removed. Pine seedlings were planted in July 1985 and the entire experiment was maintained weed-free for the first 3 years after planting. Logging residue in the residue-and-litter-retained treatment was sampled from eight quadrats (0.25 m^2) per plot (n=4). At the same time, litter was sampled from 16 quadrats (0.1 m^2) per plot in the litter-only treatment. Six soil cores per plot were bulked for each depth (0–0.15, 0.15–0.30, 0.30–0.50, and 0.50–1.60 m), air-dried, and sieved (2 mm). Both <2-mm and >2-mm size fractions were retained for analysis. Temporal variation in soil (0–0.15 m) carbon was assessed periodically on a composite sample of 16 cores (50 mm internal diameter) per plot. These samples were not sieved prior to analysis.

4. Thinning

The objective of this study was to examine the effects of thinning, residue management, and post-thinning fertiliser applications on site nitrogen and carbon dynamics. The experiment was situated in a second-rotation *P. radiata* plantation, planted in July 1977 and thinned in November 1988. Various treatments were subsequently imposed but only two will be referred to here—zero residue (thinned and residue removed), and normal residue (thinned and residue retained). Thinning residue was sampled from eight quadrats (0.25 m^2) per plot (n=4) in the normal-residue treatment. At the same time, litter was sampled from eight quadrats (0.25 m^2) per plot in the zero-residue treatment. Fourteen soil cores per plot were bulked for each depth (0–0.75 m in 0.15-m increments), air-dried, and half the sample sieved (2 mm). Both <2-mm and >2-mm size fractions, and the whole soil, were retained for analysis.

CARBON AND SOIL PROPERTIES/PROCESSES

Unless otherwise stated, all soil analyses reported in this paper refer to material which passed through a 2-mm sieve (i.e., <2 mm). Organic matter >2 mm is composed of material of diverse origin, including woody debris, charcoal, roots, and fungal hyphae/mycelium. The contribution of this material to "soil" carbon is significant, representing up to 35% of the total (Table 2). The decision to include or exclude the >2-mm fraction is an important one. In studies which attempt to follow changes in soil organic matter with time, e.g., after clearfelling, an artefact may be introduced if soil is sieved, since some material which will initially fail to pass a 2-mm mesh may contribute to the <2-mm fraction as decomposition proceeds.

TABLE 2–Contribution of different size fractions to soil carbon at two depths in the thinning study, n = 16, standard errors in parentheses.

	Concentrations Organic C (mg/g)		Amounts Organic C (Mg/ha)	
	0–0.15 m	0.15–0.30 m	0–0.15 m	0.15–0.30 m
Unsieved	11.0 (0.6)	4.4 (0.3)	22.3 (1.4)	11.3 (0.8)
<2 mm	7.6 (0.4)	3.1 (0.2)	14.7 (0.9)	7.8 (0.5)
>2 mm	80.5 (6.5)	83.5 (7.1)	7.0 (0.5)	3.9 (0.3)

Clay contents of these sandy soils are usually less than 2% (Stephens *et al.* 1941) and carbonate concentrations are also low. A comprehensive study of 39 podsolised sands from south-east South Australia (Lowther *et al.* 1990) showed that carbon concentrations could be accurately estimated from loss on ignition values according to the relationship:

$$\text{Organic carbon (\%)} = \text{Loss on ignition (\%)} \times 0.457$$
$$(r^2 = 0.99, p < 0.0001).$$

Nitrogen and Phosphorus

Virtually all soil nitrogen is organically bound and this is reflected in a strong linear relationship between total nitrogen and carbon (Fig. 2a). Thus, loss of carbon will lead directly to loss of nitrogen. However, nitrogen mineralisation is not well correlated with total nitrogen (Fig. 2b), suggesting that organic matter composition is important in influencing the amount of nitrogen mineralised across a range of sandy soils. In contrast to nitrogen, organic phosphorus is poorly correlated with carbon (Fig. 2c) or nitrogen. Despite this, organically bound phosphorus may exert an important control on nitrogen mineralisation in sandy soils (Fig. 2d). Alternatively, organic phosphorus may simply be a surrogate for the pool of labile organic nitrogen mineralised during incubation, with other variables governing the size and activity of this pool (*see*, for example, Troelstra *et al.* 1990).

While carbon levels *per se* are poorly correlated with those of organic phosphorus, they are correlated with indices of labile phosphorus (Fig. 3), suggesting that organic matter (and therefore carbon) plays an important role in the supply of both nitrogen and phosphorus in these sandy soils.

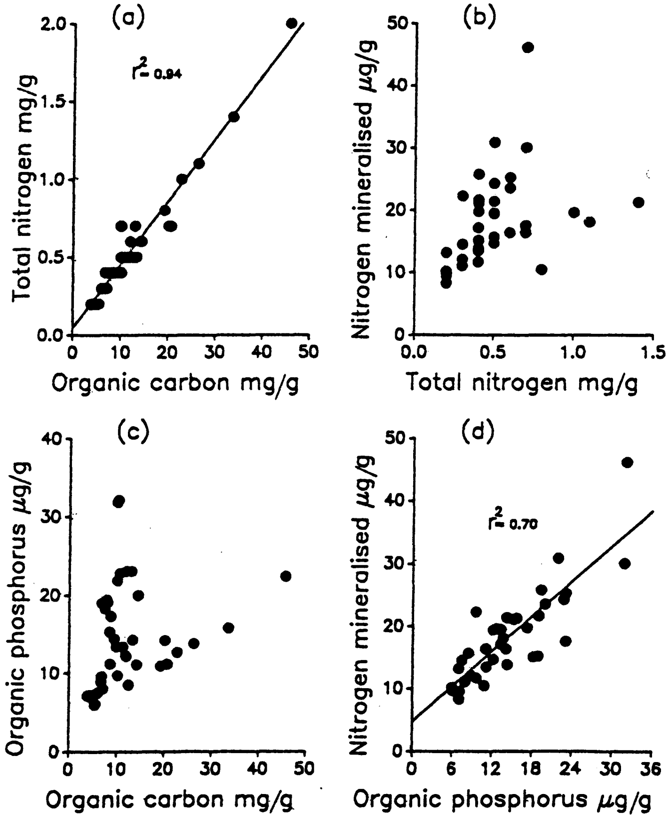

FIG. 2–Relationship between (a) organic carbon and total nitrogen, (b) total nitrogen and nitrogen mineralised (after 56 days' aerobic incubation at 15% gravimetric water content at 20°C), (c) organic carbon and organic phosphorus, and (d) organic phosphorus and nitrogen mineralised (from Carlyle *et al.* 1990). All values are for sieved (<2 mm) soil.

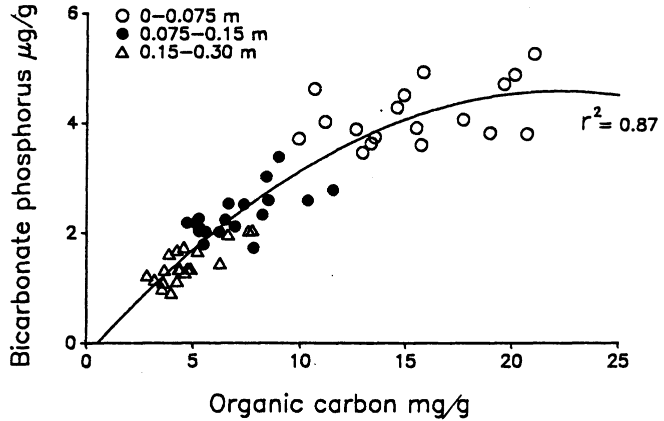

FIG. 3–Relationship between organic carbon and total bicarbonate extractable phosphorus (unsieved soil) in the thinning study. Each point represents an experimental plot, results are stratified into three depths. The regression line is a second-order polynomial of the form $Y = a_0 + a_1X + a_2X^2$ (J.C.Carlyle unpubl. data).

Cation Exchange Capacity

For the 39 soils in the ROMP study, surface-soil cation exchange capacity ranged from 11.6 to 114.9 m mol [$Ca^{+(1/2)}$]/kg (Table 1) and showed a strong positive correlation (r^2=0.91, $p < 0.001$) with carbon (J.R.Lowther, unpubl. data). These values are low in comparison with the range of 56 to 230 m mol [NH_4^+]/kg found for 17 finely textured soils (sandy loam to clay loam) under pine (Carlyle *et al.* 1989). This reflects lower organic matter concentrations and the absence of an inorganic colloidal phase in the sands.

IMPACT OF SITE PREPARATION PRACTICES ON SOIL CARBON

Weed Management

In general, the presence of weeds is detrimental to plantation growth and therefore weed control of various intensities is widely practised. Although complete weed control is commonly undertaken by some managers, strip weed control may be almost as effective in promoting tree growth while at the same time reducing early leaching of nitrogen as a result of greater plant uptake (Smethurst & Nambiar 1989). In addition, weeds can significantly influence soil carbon levels during the initial years of plantation establishment when carbon inputs from the developing plantation are minimal (Woods *et al.* 1992).

In the weed management study described above, weed biomass varied throughout the year with a maximum in spring and a minimum in summer. The above-ground carbon content of weeds in the weedy strips varied from 108 g/m^2 (summer) to 285 g/m^2 (spring), equivalent to 0.72 to 1.9 Mg/ha. Surface soil (0–0.15 m, unsieved) carbon concentrations were consistently higher in weedy strips (between the planting rows) than in the weed-free planting row (Fig. 4). Input of above- and below-ground biomass by weeds clearly maintained soil carbon levels in the 3 years after planting when inputs from the developing plantation were minimal or absent.

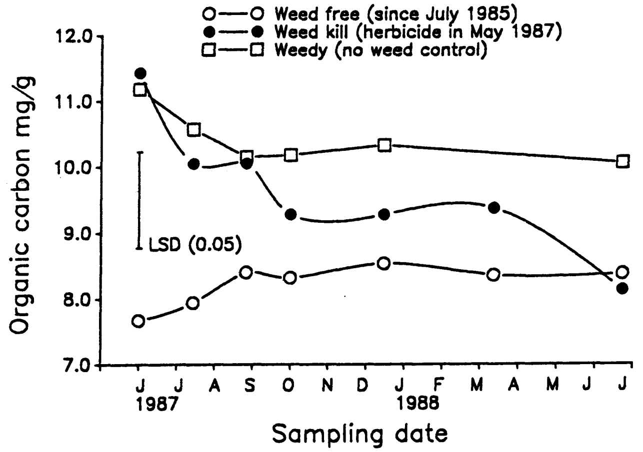

FIG. 4–Influence of weeds and weed control on soil organic carbon in the surface soil (0–0.15 m, unsieved) of the weed management study. Weed-free areas (along the planting row) = maintained free of weeds since July 1985. Weedy areas (between planting rows) = received no weed control after the area was cleared in 1984. Weed-kill areas (between the planting rows) = weeds were chemically controlled in May 1987. The LSD was calculated for the treatment × sampling date interaction (J.C.Carlyle, E.K.S.Nambiar, P.V.Woods unpubl. data).

While carbon inputs from weeds can certainly maintain soil carbon levels, with a concomitant improvement in a range of soil properties (Table 3), the nature of this material is highly dynamic. Once weeds are removed (e.g., weed kill treatment, Fig. 4) soil carbon concentrations fall rapidly, reaching the same concentration as the weed-free area within 12 months. The rapid run-down in surface soil carbon levels after weed control probably reflects (1) the non-recalcitrant nature of weed residue, and (2) the absence of physical protection of carbon in these sandy soils. In contrast, soil carbon levels in the weed-free strips remained at a relatively stable, but lower, level. These observations suggest two distinct fractions of carbon in this sandy soil—regular carbon inputs in the presence of weeds supports a labile carbon fraction which represents around 30% of the total pool, the remaining 70% comprising more stable material (typified by the weed-free strips where soil carbon levels remained relatively constant over the period of measurement despite minimal carbon inputs). The dynamic nature of the labile carbon pool means that any operations which alter carbon inputs may be rapidly reflected in a change in soil carbon concentrations, and associated soil properties (Table 3).

TABLE 3–Influence of weeds and soil depth on soil (unsieved) carbon concentration, moisture content at field capacity, nitrogen concentration, and nitrogen mineralised (during a 60-day aerobic incubation at 20°C) (J.C.Carlyle and P.V.Woods unpubl. data).

		C (mg/g)	H_2O (%)	N (mg/g)	N min (μg/g)
Weedy	(0–0.075 m)	14.0	13.8	0.68	30.0
Weed free	(0–0.075 m)	10.6	10.8	0.50	10.8
Weedy	(0.075–0.15 m)	8.7	10.6	0.38	5.7
Weed free	(0.075–0.15 m)	6.7	9.1	0.39	2.5
$LSD_{0.05}$		2.4	2.1	0.14	3.1

Residue Management

On podsolised sandy soils, residue and litter remaining after clearfelling or thinning represent a considerable portion of a site's carbon reserves (Table 4), equivalent to 123% and 63% of soil carbon (0–0.3 m, unsieved) respectively. However, thinning and clearfelling operations differ in two important respects:

(1) After clearfelling, further plant input of carbon is minimal until establishment of the next crop or development of weed cover. After thinning, above- and below-ground carbon input rates are maintained;

(2) Soil moisture and temperature are significantly increased by clearfelling, with a resultant elevation in nitrogen mineralisation (Smethurst & Nambiar 1990a) suggesting a general increase in microbial activity and carbon mineralisation. After operational thinnings in south-east South Australia, there was little change in soil moisture and temperature and no change in nitrogen mineralisation (Carlyle, unpubl. data).

Consequently, there should be greater potential for a decline in soil carbon concentrations after clearfelling, particularly where logging residues are not retained on site. This hypothesis is supported by results from the residue management study in which surface soil carbon concentrations declined significantly ($p < 0.01$) between 1985 and 1991 where residue was

TABLE 4–Distribution of site carbon after clearfelling or thinning, 50% reduction in basal area (Smethurst & Nambiar 1990a; J.C.Carlyle unpubl. data).

	Clearfelled, 37 years old		Thinned, 11 years old	
	(Mg/ha)	(% total)	(Mg/ha)	(% total)
Trees	0	0	43	47
Residue	26	34	15	16
(woody)	(20)	(26)	(11)	(12)
Litter	16	21	4	4
Soil (0–0.3 m)*	34	45	30	33
Total	76	100	92	100

* Unsieved

removed but showed no decline ($p > 0.05$) where residue was retained (Fig. 5). In 1991, 7 years after felling, surface soil carbon concentrations were significantly higher ($p < 0.01$) where residue had been retained than where residue was removed (Fig. 5). Thus, retention of above-ground logging residue can maintain soil carbon concentrations. In contrast to clearfelling, thinning had no effect on soil carbon levels during the first 4 years of measurement, reflecting the continued input of plant litter (above and below ground) and maintenance of pre-thinning decomposition rates.

The extent to which any surface organic residue becomes part of the soil carbon pool will depend on the degree of incorporation which occurs, by either physical or biological processes. Once incorporated within the soil, interaction with inorganic colloids means that subsequent decomposition may no longer be a simple function of substrate composition. Where incorporation is minimal, as a consequence of low levels of faunal activity, surface organic residues may decompose largely *in situ* without entering the soil system. Under such conditions, surface residue may not be especially effective at maintaining soil carbon concentrations and inputs through roots may be more important. Incorporating the litter by

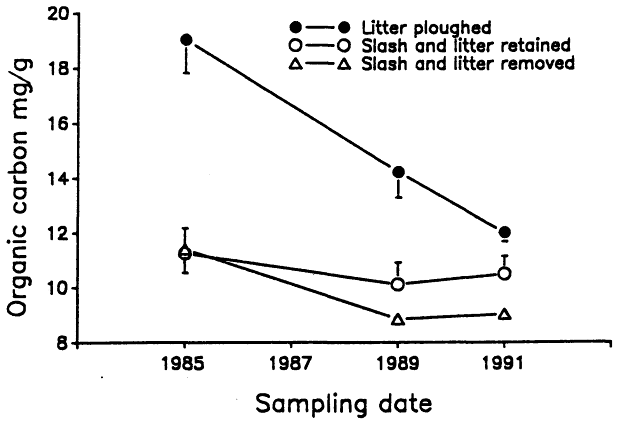

FIG. 5–Change in surface soil (0–0.15 m, unsieved) organic carbon in the residue management study under different residue treatments. Mean values (n = 4), bars show standard errors. The 37-year-old plantation was clearfelled in August 1984 and replanted in July 1985. All treatments were kept weed free (Smethurst & Nambiar 1990b; J.C.Carlyle, P.J.Smethurst, E.K.S.Nambiar unpubl. data).

ploughing greatly augments natural incorporation processes and results in elevated soil carbon levels (Fig. 5). Augmenting natural incorporation processes has the potential to increase the quantity of residue carbon which is physically stabilised through interaction with inorganic colloids.

DISCUSSION AND CONCLUSIONS

Organic matter is the principal determinant of a range of soil properties which influence tree growth in sandy soils. It is also the main reservoir of nitrogen and strongly influences nitrogen availability through differences in organic matter quantity and quality. Since approximately 45% of soil organic matter in the forested sandy soils of south-east South Australia is composed of carbon, the cycling and dynamics of this element are central to sustainable production. Carbon concentrations in sandy soils are not fixed but are highly sensitive to management operations which influence carbon inputs or alter rates of decomposition. Forest operations with the greatest potential to influence soil carbon dynamics in south-east South Australia are (1) management of residues after clearfelling or thinning, (2) management of competing vegetation, and (3) cultivation.

Unlike that in more finely textured soils, only a small proportion of the carbon in sandy soils is likely to be stabilised as organo-mineral complexes in soil aggregates; rather, carbon will be chemically stabilised through the formation of recalcitrant compounds. In finely textured soils a significant portion of carbon, although readily decomposable in terms of its chemical characteristics, is rendered resistant to microbial attack by physical protection within soil aggregates (Paul 1984). The type, content, and extent of aggregation are recognised as dominant factors controlling carbon dynamics in fine textured soils (Tisdall & Oades 1982). Some 36% of soil carbon may be physically stabilised (Paul 1984), greatly increasing the residence time of material which may otherwise decompose relatively rapidly, e.g., the decomposition rates of a range of organic substances have been shown to decline in the presence of allophane (Zunino *et al.* 1982) while labile organic compounds released during the initial phase of decomposition can also be stabilised by clay (Sorensen 1983). Such physical protection, when coupled with chemical stabilisation, means that carbon levels in finely textured soils are comparatively well buffered against short-term changes in carbon inputs and decomposition rates (Skjemstad & Dalal 1987). Additional stabilisation of carbon in soils may occur through the association of low molecular weight humic substances with metals such as iron and, particularly, aluminium (Blaser & Klemmedson 1987; Skjemstad & Dalal 1987), and by trapping of non-humic substances in voids of high molecular weight polymers (Ruggiero *et al.* 1981).

Only a small fraction of the carbon added to a sandy soil will become chemically stabilised (i.e., have a long residence time). Most will decompose relatively rapidly, being lost as carbon dioxide at rates governed by environmental factors and substrate quality. Carbon levels in sandy soils are likely to be more sensitive to changes in carbon inputs and decomposition rates than carbon levels in more finely textured soils. While the chemically stabilised portion of soil carbon is likely to remain relatively constant, the non-stabilised fractions will be highly dynamic and are likely to fluctuate if decomposition or input rates are altered through management operations. This hypothesis fits well with the rapid fall in soil carbon levels after weed control noted in the weed management study (Fig. 4). Since this active fraction may represent around 30% of the carbon pool (Fig. 4) its loss due to cessation of inputs, elevated decomposition rates, or both, is associated with changes in related soil properties such as moisture holding capacity, nitrogen concentration, and nitrogen mineralised (Table 3). However, there is no reason to suppose that this fraction cannot be re-established on resumption of carbon inputs, and so the impact of some harvesting or site-preparation operations may be transient and reversible. Loss from the more recalcitrant pool would take much longer to replace and could result in a long-term reduction in soil carbon and associated properties. Agren & Bosatta (1987) have speculated that carbon levels in soil are controlled by litter of the lowest initial quality (i.e., woody residues), and that continued removal of such material by harvesting operations may lead to long-term depletion of soil carbon reserves. Since such material decomposes extremely slowly, only site preparation operations such as surface soil scalping or use of high-intensity fire are likely to result in significant losses from this pool in the short term.

Softwood plantations in south-east South Australia have all been established during the past 100 years. The previous vegetation supported by the soils was open sclerophyll forest of low productivity which was subjected to frequent fires resulting in loss of accumulated carbon. *Pinus radiata* produces a biomass well above that of the original native forest (Squire 1983). Furthermore, input of carbon in woody material (wood + bark + cones) after clearfelling of a 37-year-old stand was 20 Mg/ha (Table 4), which is 2.3 to 5.7 times the input that would occur as woody litter from native forest (calculated from Hutson 1985) during a similar period. At first thinning the input of carbon in woody residue can be 11 Mg/ha (Table 4) and stands can receive several thinnings during a rotation. Therefore, despite the removal of recalcitrant woody material in stems, woody litter inputs under managed forest will be substantially greater than under native forest in this region. Assuming that a similar proportion of woody litter enters the chemically stabilised pool in both forest types, then soil carbon levels may actually increase under plantations, so long as residues are retained.

Because sands lack the complication of physically stabilised carbon, they represent a sensitive and relatively simple system with which to test the effect of forest operations on soil carbon dynamics, and an ideal system for initial verification of carbon cycling models.

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