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Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand

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Abstract

Labile organic matter fractions (light fraction C, microbial biomass C and water-soluble organic matter) were extracted from two soils (Lismore silt loam and Temuka clay loam) varying in cropping history from long-term (> 9 yr) arable cropping to long-term (> 9 yr) pasture in the Canterbury region of New Zealand. With increasing periods under pasture, soil organic C content increased and the amounts of labile organic matter extracted increased (microbial biomass C, 1.0–2.2% of organic C; light fraction, 1.8–4.6% organic C and water-soluble C, 0.7–1.2% organic C). Labile organic matter was more closely correlated with previous cropping history (R = 0.89–0.96) than with soil organic C content (R = 0.81–0.82). Alternating these soils under rotations of 2–5 yr of pasture followed by 2–5 yr arable resulted in soil organic C remaining unchanged while labile organic matter increased under pasture and declined under the arable phase. The three indices of labile organic matter were closely correlated suggesting they are interrelated properties. In the Lismore soil the mean proportion of total soil organic C, N and P present in water-soluble form differed widely being 0.28, 0.18 and 0.03% respectively for field-moist samples. This presumably reflects differences in chemical nature, solubility, biodegradability and affinity for soil colloids of soil organic C, N and P compounds. Water-soluble organic C, N and P was much greater when extracted from air-dried than field-moist soils and this difference was proportionately greater for soils with higher total soil organic matter contents. Water-soluble organic matter in air-dried soils was thought to have originated from soil solution, from lysed desiccated microbial cells and from labile humic material. It was concluded that inclusion of grazed pastures in a cropping system maintains labile organic C in higher amounts than is possible under annual cropping. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Labile organic matter; Light-fraction C; Pasture; Arable soils

1. Introduction

Management induced changes in soil organic matter status that occur over relatively short periods (e.g. 1–5 yr) are difficult to measure due to large background amounts of relatively stable soil organic matter that are already present (Gregorich et al., 1994). By contrast, because of their dynamic nature, labile fractions of organic matter such as microbial biomass C, light fraction C and easily extractable or mineralizable C pools can respond rapidly to changes in C supply. Such components have therefore been suggested as early indicators of the effects of soil management and cropping systems on soil organic matter quality (Gregorich et al., 1994; Haynes and Beare, 1996). They are also considered to be important indicators of soil quality (Doran and Parkin, 1994).

Dissolved organic matter is a labile fraction that has received little attention in agricultural soils. Research on dissolved organic C has concentrated on its role as an immediately available C resource from decaying forest litter, its leaching through soils as a pedogenic

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process and its subsequent effect on the quality of ground and stream water (Cook and Allan, 1992; Qualls and Haines, 1992; Christ and David, 1996). Water-soluble organic matter is, however, an important labile fraction since it is the main energy source for soil microorganisms, it is a primary source of mineralizable N, P and S and it influences the availability of metal ions in soils by forming soluble complexes (Stevenson, 1994).

The Canterbury region of New Zealand is the main area for arable crop (mainly wheat and barley) production in the country. Although some fields have been under arable crops for long periods (e.g. > 10 yr), the predominant farming system is mixed cropping where arable crops are grown for about 2–5 yr in rotation with about 2–5 yr of grazed grass–clover pasture. There are also dairy farms in the area which are under long-term (> 10 yr) pasture. My purpose was to investigate how soil organic matter quality, as estimated using labile organic matter fractions (i.e. light fraction C, microbial biomass C and water-soluble organic matter), is influenced by the various farming systems. In particular, changes in water-soluble organic C, N and P, extracted from both field-moist and air-dried soils, were studied and compared with those for other labile fractions. The relationship between labile organic C fractions and total organic matter or, alternatively, an index of previous cropping history, was also investigated.

2. Materials and methods

Samples of the surface horizon (0–10 cm) of two soil types from the Canterbury region, N.Z. were used in the study (Kear et al., 1967). The soils were Lismore silt loam (Udic Ustochrept, USDA; Dystric Cambisol, FAO) and Temuka clay loam (Mollic Haplaquept, USDA; Mollic Gleysol, FAO). The Lismore soil has a clay content of about 240 g kg^{-1} and Temuka about 380 g kg^{-1}. The clay fractions are dominated by illite with some interstratified minerals and vermiculite being present.

Samples were taken from farmer's fields in spring (September). The previous cropping history of each field over the last 5–15 yr was recorded. Sites were chosen to give a reasonable spread of histories ranging from long-term arable cropping to long-term pasture. Twenty sites were sampled on the Lismore soil and 22 on the Temuka soil. Data collected on cropping history was incorporated into a cropping index using an eight-part scale (Haynes et al., 1991). The index numbers refer to (1) > 9 yr arable, (2) 6–9 yr arable, (3) 3–6 yr arable, (4) 0–3 yr arable, (5) 0–3 yr pasture, (6) 3–6 yr pasture, (7) 6–9 yr pasture and (8) > 9 yr pasture.

In a subsidiary study, soil samples (0–10 cm) were taken from four fields situated close to one another on the AgResearch Winchmore Irrigation Research Station in mid-Canterbury. These fields were on Lismore silt loam and had known contrasting cropping histories. Two had long-term histories of monoculture; (i) 20 yr pasture and (ii) 15 yr arable. The other two fields had a history of alternating arable and pasture management. The immediate past cropping histories of these fields were (i) 5 yr arable followed by 4 yr pasture and (ii) 6 yr pasture followed by 4 yr arable.

Samples of both Lismore and Temuka soils were analysed for organic C and labile organic C fractions and for the Lismore soil, total N, organic P and water-soluble organic N and P were also measured. Samples of field-moist soil (soil water content = 0.23–0.26 g g^{-1}) were sieved (< 2 mm). A subsample was air-dried for 48 h and ground (< 150 μm) for analysis of organic C, total N and organic P. Soil organic C was determined colorimetrically by the Walkley and Black technique (Blakemore et al., 1972), total N by semimicro Kjeldahl digestion (Bremner and Mulvaney, 1982) and organic P by an ignition method (Olsen and Sommers, 1982). Field-moist samples were stored at 4°C for up to 10 d prior to analysis. Microbial biomass C was estimated by the fumigation-extraction method using a K_c factor of 0.38 (Vance et al., 1987). Water-extractable organic C, N and P were extracted with 20 ml distilled water from both field-moist and air-dried samples (10 g oven-dried equivalent) for 15 min and then centrifuged at 15 000 rpm for 10 min. The supernatant was filtered through a 41 μm Millipore filter. Filtrates were stored at −10°C until analysed. Organic C in extracts was measured by a dichromate oxidation procedure involving boiling under refluxing conditions for 30 min (Vance et al., 1987) and organic P as the difference between inorganic P measured by the molybdenum blue method (John, 1970) before and after digestion with nitric and perchloric acids. Organic N was measured as the difference between NH_4^+-N measured before and after Kjeldahl digestion of extracts.

The light fraction was isolated from sieved (< 2 mm) field-moist soil by the method of Gregorich and Ellert (1993) using a NaI solution (sp. gr. = 1.70). Two successive extractions of 60 min were used (1:2 soil:extractant ratio), the isolated light fraction was air-dried at 70°C and the organic C content was determined as outlined above.

Data relating the various measured properties were fitted to linear, quadratic and cubic functions. Quadratic and cubic functions did not give significantly better fits to the data than linear functions and consequently only linear functions are reported in this paper.

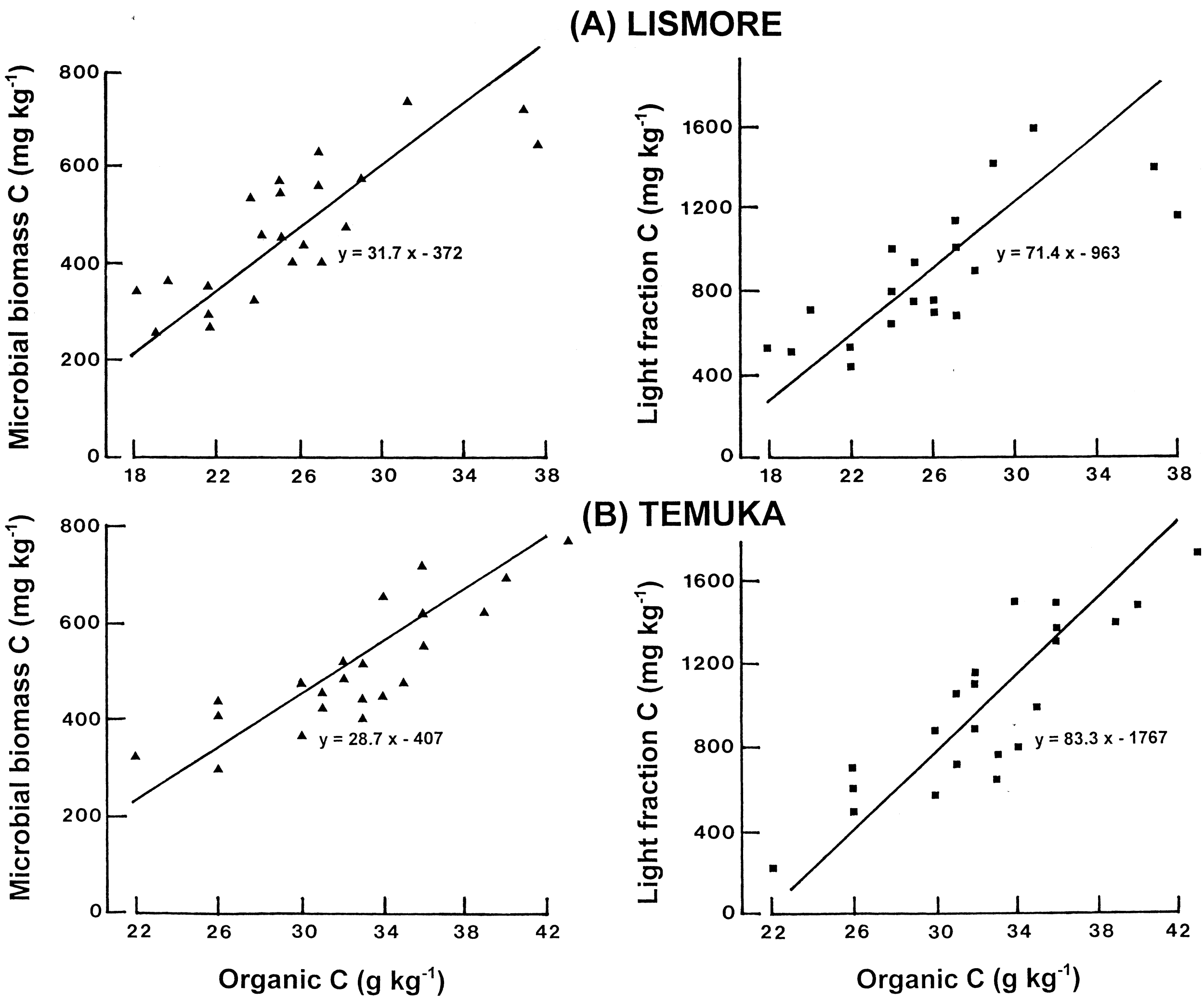

Fig. 1. Relationship between organic C content and microbial biomass C or light fraction C for the (A) Lismore and (B) Temuka soils. Linear regression equations and lines of best fit shown.

Table 1
Linear correlation coefficients (R) between cropping index, organic C and various pools of labile organic C; statistical significance shown: $^{**}P \leq 0.01$, $^{***}P \leq 0.001$

Soil type and measurement	Organic C	Soluble C (air-dried)	Soluble C (field-moist)	Light fraction C	Microbial biomass C
Lismore (n=20)					
Cropping index	0.81***	0.94***	0.89***	0.92***	0.95***
Microbial biomass C	0.78**	0.90***	0.85***	0.90***	
Light fraction C	0.73**	0.85***	0.81***		
Soluble C (field-moist)	0.69**	0.83***			
Soluble C (air-dried)	0.80***				
Temuka (n=22)					
Cropping index	0.82***	0.95***	0.91***	0.96***	0.95***
Microbial biomass C	0.77**	0.90***	0.85***	0.93***	
Light fraction C	0.82***	0.90***	0.83***		
Soluble C (field-moist)	0.78**	0.90***			
Soluble C (air-dried)	0.77**				

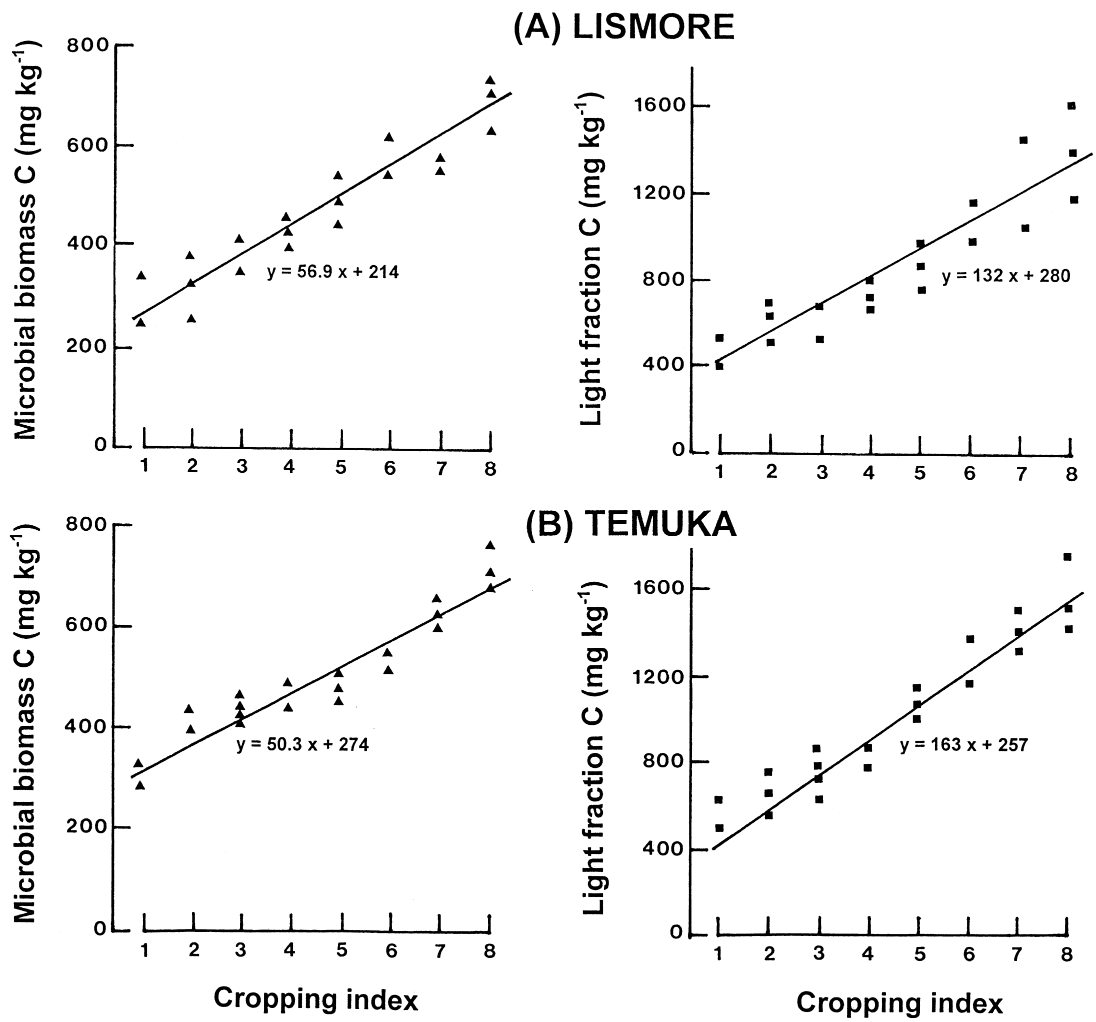

Fig. 2. Relationship between cropping index and microbial biomass C or light fraction C for the (A) Lismore and (B) Temuka soils. (1) > 9 yr arable; (2) 6–9 yr arable; (3) 3–6 yr arable; (4) 0–3 yr arable; (5) 0–3 yr pasture; (6) 3–6 yr pasture; (7) 6–9 yr pasture and (8) >9 yr pasture. Linear regression equations and lines of best fit shown.

3. Results

Mean field bulk density in the 0–10 cm layer was 1.4 Mg m^{-3} for Lismore and 1.6 Mg m^{-3} for the Temuka soil. No significant trends were measured for bulk density with increasing organic C content because the soils with a high organic matter content were under dairy pasture and thus subject to trampling, whilst most of the arable fields had been cultivated and therefore possessed a substantial interclod porosity. In addition, the Lismore A horizon contains a significant portion of stones. Thus, results are presented here on a mass basis.

Microbial biomass C and light fraction C increased linearly with increasing soil organic C content for both the Lismore and Temuka soils (Fig. 1). The organic C content of samples of Temuka soil (range = 22–43; mean = 33 g C kg^{-1}) was generally higher than that for the Lismore samples (range = 18–38; mean = 26 g C kg^{-1}). The microbial quotient (proportion of total soil organic C present as microbial biomass C) increased from 1.3 to 2.2% as organic C increased from 18 to 38 g C kg^{-1} for the Lismore soil and from 1.0–1.8% as organic C increased from 22 to 42 g C kg^{-1} for the Temuka soil. Corresponding increases in the ratio of light fraction C to organic C were 1.8–4.6% for Lismore and 3.0–4.1% for Temuka whilst those for the ratio of water-soluble C (air-dried soil) to organic C were 0.9–1.1% for Lismore and 0.7–1.2% for Temuka soil.

As illustrated by comparing the spread of data points in Figs. 1 and 2, both microbial biomass C and light fraction C were more closely related to cropping index than organic C content. Indeed, regression analysis of the data (Table 1) showed that microbial biomass C, light fraction C and water-soluble C were all more closely correlated with cropping index than organic C content for samples of both of the soils

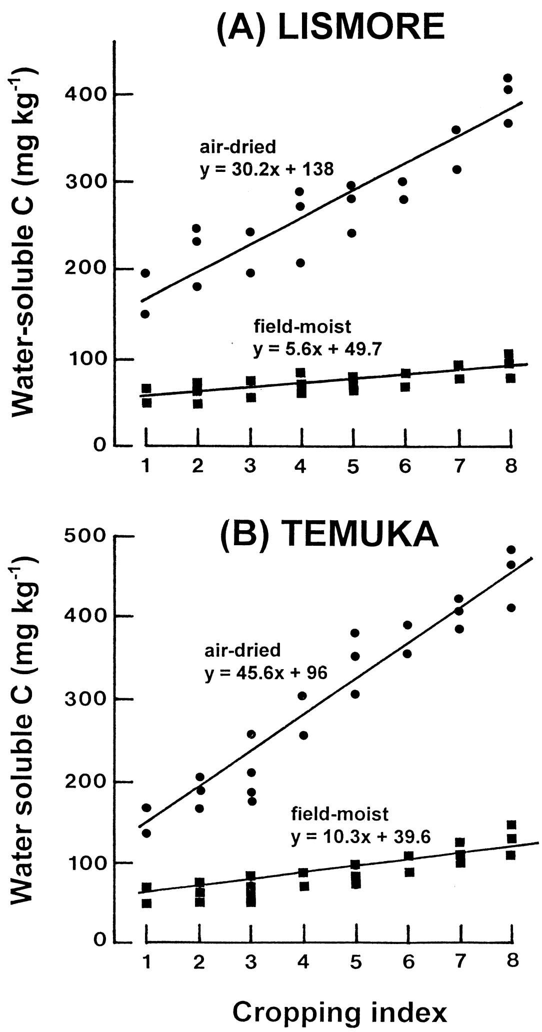

Fig. 3. Relationship between cropping index and water-soluble C extracted from air-dried and field-moist samples for the (A) Lismore and (B) Temuka soils. (1) > 9 yr arable; (2) 6–9 yr arable; (3) 3–6 yr arable; (4) 0–3 yr arable; (5) 0–3 yr pasture; (6) 3–6 yr pasture; (7) 6–9 yr pasture and (8) >9 yr pasture. Linear regression equations and lines of best fit shown.

used. There was a tendency for microbial biomass C to be higher for the Temuka than Lismore soil at the same cropping index (Fig. 2). For example, as cropping index increased from 1 to 8, microbial biomass C increased from 260 to 675 mg C kg^{-1} for the Lismore soil (mean = 470 mg C kg^{-1}) and from 325 to 696 mg C kg^{-1} for the Temuka soil (mean = 502 mg C kg^{-1}).

Water-soluble C increased linearly with increasing cropping index (Fig. 3) for both the Lismore and Temuka soils and air-drying the samples caused a very marked increase in the quantity of water-soluble C that was extracted. This increase in extractability was proportionately greater at higher cropping index values (Fig. 3) or higher organic C contents (data not presented) and, as a result, the separation of values between low and high cropping indices was much more pronounced when water-soluble C was extracted from air-dried samples. A similar trend was evident for water-soluble organic N and P for the Lismore soil (Fig. 4).

As expected, both total N and soil organic P increased with increasing cropping index (Fig. 4) and both were closely correlated with organic C content ($R = 0.96^{***}$ and 0.97^{***}, respectively). Whilst water-soluble organic N and P were significantly correlated with total N and organic P content of soils respectively, they were more closely correlated with cropping index. For example, correlation coefficients between water-soluble N and total N were 0.84^{***} and 0.81^{***}, respectively for field-moist and air-dried samples but those between water-soluble N and cropping index were 0.90^{***} and 0.91^{***}, respectively.

Water-soluble organic C, N and P represented widely differing proportions of total soil organic C, N and P respectively (Table 2). It is evident from Table 2 that soluble C represented the greatest proportion, whilst soluble organic P made up the least proportion. For air-dried samples, the proportion of organic C, N or P that was water-soluble increased markedly with increasing cropping index (Table 2).

Data presented in Table 3 shows the effect of previous cropping history on organic C and labile organic C fractions. As expected, the long-term pasture site had high values for all variables while the long-term arable site had low values. Nevertheless, the 5 yr arable–4 yr pasture and 6 yr pasture–4 yr arable sites had

Table 2
Effect of air-dried versus field-moist samples and cropping index on the mean percentage of total element present in soil organic form that is extractable with water from the study soils

Cropping index	Lismore						Temuka	
	Organic C		Total N		Organic P		Organic C	
	Air-dried	Field-moist	Air-dried	Field-moist	Air-dried	Field-moist	Air-dried	Field-moist
> 9 yr arable	0.85	0.28	0.55	0.17	0.19	0.02	0.55	0.19
0–3 yr pasture	1.08	0.28	0.76	0.18	0.33	0.03	0.96	0.29
> 9 yr pasture	1.17	0.29	0.88	0.19	0.40	0.04	1.19	0.32

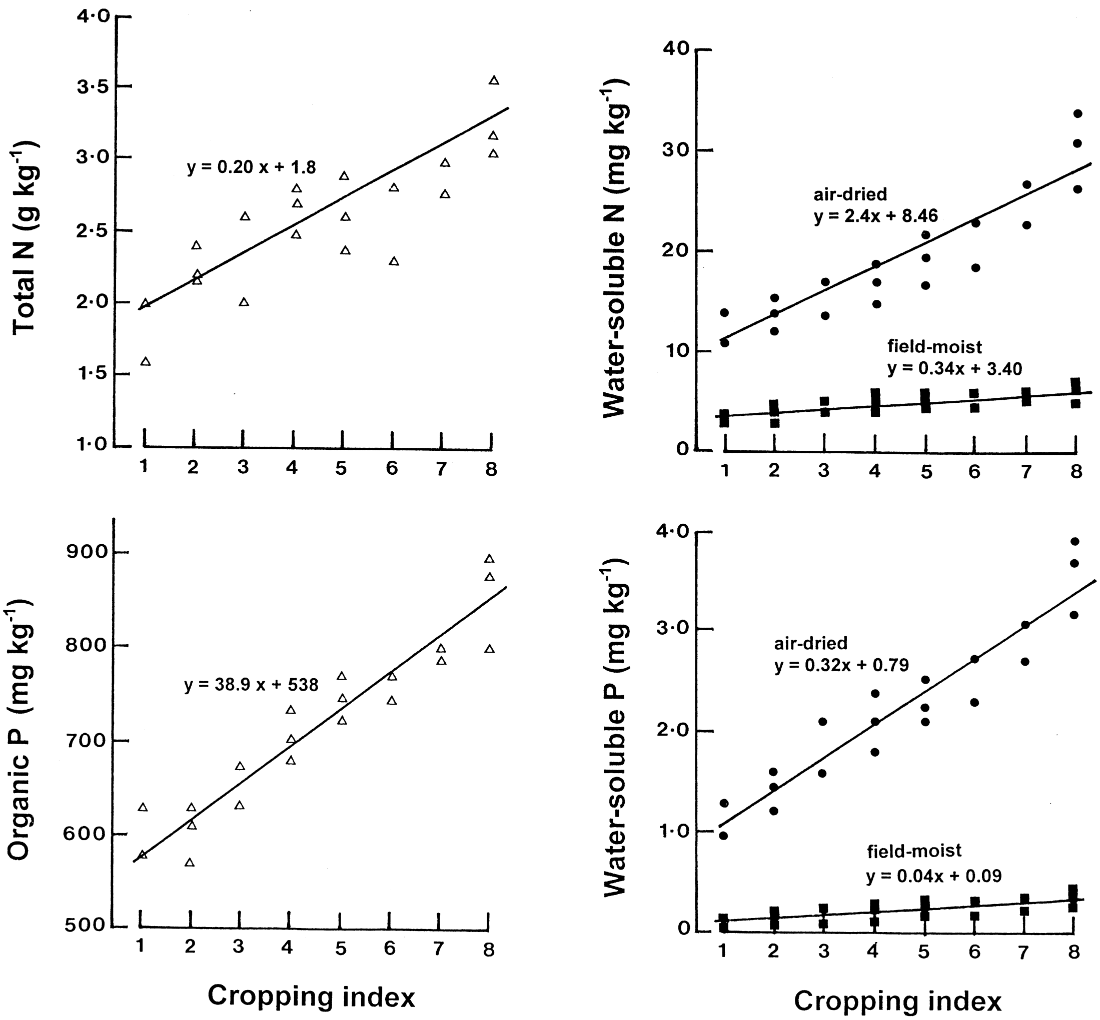

Fig. 4. Relationship between cropping index and total N and organic P or water-soluble organic N and P extracted from air-dried and field-moist samples for the Lismore soil. (1) > 9 yr arable; (2) 6–9 yr arable; (3) 3–6 yr arable; (4) 0–3 yr arable; (5) 0–3 yr pasture; (6) 3–6 yr pasture; (7) 6–9 yr pasture and (8) >9 yr pasture. Linear regression equations and lines of best fit shown.

identical organic C contents but values for labile organic matter (light fraction, microbial biomass and water-soluble C) were considerably higher for the pasture than arable site.

4. Discussion

Long-term pasture samples have a considerable higher total soil organic C, N and P content, water-

Table 3
Effect of cropping history on organic, light fraction, microbial biomass and water-soluble C in a Lismore soil

Previous cropping history	Cropping index	Organic C (g kg^{-1})	Light fraction C (mg kg^{-1})	Microbial biomass C (mg kg^{-1})	Water-soluble C (mg C kg^{-1})	
					Field-moist	Air-dried
20 yr pasture	8	34	1350	791	106	426
5 yr arable–4 yr pasture	6	26	990	570	86	310
6 yr pasture–4 yr arable	3	26	620	384	75	231
15 yr arable	1	20	501	272	62	194

soluble organic C, N and P, microbial biomass C and light fraction C content than their long-term arable counterparts. This reflects the build-up of organic matter under pasture and its breakdown under arable conditions. Organic matter additions under pasture arise from senescing plant roots and tops, exudation of organic compounds from pasture roots, turnover of the large microbial biomass in the pasture rhizosphere and return of ingested material by grazing animals mainly in the form of dung (Haynes and Williams, 1993). Under arable cropping, the amount of organic material returned to the soil is much less than under pasture and, in addition, the soil is often tilled several times per year which favours decomposition of native soil organic matter (Haynes and Beare, 1996).

The fact that the labile soil organic matter fractions measured (light fraction C, microbial biomass C and water-soluble C) were significantly correlated with organic C content suggests that, as expected, total soil organic matter content was a major determinant of the amount of labile organic matter present. Nonetheless, at a given soil organic C content, there can be a considerable range of values for labile organic matter depending primarily on the immediate past cropping history (arable or pasture) of the field. Due to changes in C supply, labile organic matter fractions can increase markedly under the pasture phase of crop–pasture rotations and decline under the arable phase even though total organic C remains unchanged (Table 3). Similar fluctuations in microbial biomass C have been demonstrated during a rotation of 4 yr pasture followed by 4 yr of arable cropping (Haynes et al., 1991). Since cropping index is a measure of the number of years a soil has been under pasture or arable cropping immediately prior to sampling, it is more closely correlated with labile organic matter than total organic C content.

Such results reflect the dynamic nature of labile soil organic matter in soils of the study area which often alternate between arable and pastoral management. Fluctuations in soil organic matter quality are likely to influence both soil physical and biological properties. Indeed, studies in the locality have shown that both aggregate stability and the size of the earthworm community are better correlated with cropping index than soil organic C content (Haynes et al., 1991; Fraser et al., 1996). A drawback of this empirical cropping index approach is that whilst it works well for pasture–arable rotations, it is not readily transferable to other cropping systems. A more mechanistic index relating labile organic matter contents to factors such as crop C inputs, percentage of the season where metabolically active roots are present and partitioning of above- and below-ground biomass between annual and perennial plants will be required if comparisons between different cropping systems are being made.

It is not surprising that the three measures of labile organic matter used were closely correlated with one another since they are closely interrelated properties. The light fraction represents a transitory pool between fresh residues and humified stable organic matter (Gregorich and Janzen, 1996). It acts as a reservoir of relatively labile C which supplies the soluble C pool. A large portion of the microbial community is associated with the light fraction and soil respiration rates are often correlated with the light fraction C content (Gregorich et al., 1994; Gregorich and Janzen, 1996). Water-soluble C is the primary energy source for the microbial biomass although, in turn, microbial metabolites (e.g. polysaccharide mucilage) contribute significantly to the soluble C pool (Cook and Allan, 1992; Qualls and Haines, 1992).

The protecting effect of clay on organic matter, through formation of organic–mineral complexes, is evident from the higher organic C content for the Temuka than Lismore soil. Although the higher clay content also resulted in a tendency for a higher microbial biomass, the increase was less than that for organic C. As a result, the microbial quotient was lower in the Temuka soil. Sparling (1992) also observed a similar effect with increasing clay content for volcanic ash soils containing allophanic clays. The stabilizing effect of clays probably means that soils with a higher clay content contain a larger proportion of inert organic matter; thus there is a decrease in microbial quotient.

A marked increase in microbial quotient with increasing soil organic C content was also noted by Haynes and Tregurtha (1998). The reason for it is probably that soils with a high soil organic matter content were from under long-term pasture. The large quantities of readily mineralizable organic material (e.g. labile organic C) added to soils under permanent pasture means that a proportionately higher microbial biomass can be supported than that under long-term arable management. Certainly, as organic C increased from that under long-term arable to that under long-term pasture, the proportion of total soil organic C present in labile form (i.e. as light fraction or water-soluble C) also increased.

Dissolved organic matter enters the soil as leachate from decaying above-ground herbage or incorporated crop residues, when living roots and soil microbes exude metabolic products (e.g. mucigel) or when they decompose in the soil (Cook and Allan, 1992; Qualls and Haines 1992). The concentration of dissolved organic matter retained in soil solution is dependent on its rate of supply, its rate of degradation and the adsorption characteristics of the soil (Christ and David, 1996). The widely differing proportions of total organic C, N and P that are present in water-soluble form presumably reflects differences in the chemical nature of organic C, N and P in soils and differences in water-solubility, biodegradability and affinity for soil colloids. Dissolved organic N and P represent labile, readily — mineralizable pools that will be important to the availability of these nutrients particularly in unfertilized soils. It will, however, be the rate of turnover of N and P through these pools that will be the important determinant of availability rather than the amount present at any one time.

The nature of organic matter extracted from air-dried soils with water is unclear. An increase in water-soluble C following air-drying has been observed by other workers (Davidson et al., 1987; Bolan et al., 1996). Davidson et al. (1987), for instance, reported 2- to 10-fold increases in water-extractable C when forest soils from North Carolina were air-dried. Such increases are partially derived from lysis of the microbial biomass that is killed by desiccation (West et al., 1992). Assuming that about 40 % of the soil microbial biomass is killed by air-drying and a maximum of 50% of the microbial C is easily extractable (Sparling et al., 1986; West et al., 1992) then about 50% of the increase in soluble C induced by air-drying can be explained as microbial C (i.e. 58 and 45%, respectively, at cropping indices of 1 and 8 for Lismore soil). Solubilized C can also be derived from soil humic material since drying causes the macromolecules of soil organic matter to change into a highly condensed state. Such shrinkage of organic matter results in disruption of organo–mineral associations with the subsequent release of some low molecular weight humic components (Haynes and Swift, 1991).

Increases in extractable mineral P and N in soils following drying are believed to be derived primarily from mineralization of desiccated microbial cells (Sparling et al., 1985; Sparling and Ross, 1988). The increases in extractable organic P and N observed in my study are also likely to be derived from lysis of dead microbial cells as well as from solubilized humic material.

Further work is warranted to characterize the nature of soluble organic C extracted from air-dried soils. As noted previously, the C extracted apparently originates from soil solution, from lysed dead microbial cells and from labile humic material. Measured values are, therefore, the result of extraction from several different important labile pools of soil organic matter and between cropping indices 1–8, the range of values extracted from air-dried samples was 1.5 times that extracted from field-moist ones. Values clearly differentiated between different cropping histories and a further evaluation of the extraction procedure for use as an index of soil quality is warranted.

Because of its dynamic nature, microbial biomass C has been promoted as an indicator of early changes in soil organic matter status brought about by management practices such as tillage (Carter, 1986), straw incorporation (Powlson et al., 1987) or, as shown in this study, cropping history. Similarly, light fraction C has been used as an indicator since it is rapidly depleted when a soil is brought under cultivation and rapidly increases when a degraded soil is put under a continuous forage crop (Gregorich et al., 1994; Gregorich and Janzen, 1996). My results demonstrate that water-soluble C is another labile fraction that can be used as an indicator of short-term changes in C status of soils. As exemplified by the close correlations between labile organic matter fractions and cropping index, an index of the cropping history of a soil immediately prior to sampling can also give a reasonable indication of organic matter quality. Such an empirical index may therefore have some value in soil quality evaluation.

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References

Blakemore, I.C., Searle, P.L., Daly, B.K., 1972. Methods of Chemical Analysis of Soils. New Zealand Soil Bureau Report 10A. Government Printer, Wellington.

Bolan, N.S., Baskaran, S., Thiagarajan, S., 1996. An evaluation of the methods of measurement of dissolved organic carbon in soils, manures, sludges and stream water. Communications in Soil Science and Plant Analysis 27, 2723–2737.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-total. In: Page, A.L. (Ed.), Methods of Soil Analysis, Part 2. Soil Science Society of America, Madison, pp. 595–642.

Carter, M.R., 1986. Microbial biomass as an index for tillage-induced changes in soil biological properties. Soil and Tillage Research 7, 29–40.

Christ, M.J., David, M.B., 1996. Dynamics of extractable organic carbon in Spodosol forest floors. Soil Biology & Biochemistry 28, 1171–1179.

Cook, B.D., Allan, D.L., 1992. Dissolved organic carbon in old field soils: compositional changes during the biodegradation of soil organic matter. Soil Biology & Biochemistry 24, 595–600.

Davidson, E.A., Galloway, L.F., Strand, M.K., 1987. Assessing available carbon: comparison of techniques across selected forest soils. Communications in Soil Science and Plant Analysis 18, 45–64.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.E., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America, Madison, pp. 3–21.

Fraser, P.M., Williams, P.H., Haynes, R.J., 1996. Earthworm species, population size and biomass under different cropping systems across the Canterbury Plains, New Zealand. Applied Soil Ecology 3, 49–57.

Gregorich, E.G., Ellert, B.H., 1993. Light fraction and macro organic matter in mineral soils. In: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis. Canadian Society of Soil Science, Lewis, Boca Raton, pp. 397–407.

Gregorich, E.G., Janzen, M.H., 1996. Storage of soil carbon in the light fraction and macro organic matter. In: Carter, M.R., Stewart, B.A. (Eds.), Advances in Soil Science. Structure and Organic Matter Storage in Agricultural Soils. CRC Lewis, Boca Raton, pp. 167–190.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M., Ellert, B.H., 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Canadian Journal of Soil Science 74, 367–385.

Haynes, R.J., Beare, M.H., 1996. Aggregation and organic matter storage in meso-thermal, humid soils. In: Carter, M.R., Stewart, B.A. (Eds.), Advances in Soil Science. Structure and Organic Matter Storage in Agricultural Soils. CRC Lewis, Boca Raton, pp. 213–262.

Haynes, R.J., Swift, R.S., 1991. Concentrations of extractable Cu, Zn, Fe and Mn in a group of soils as influenced by air- and oven-drying and rewetting. Geoderma 49, 319–333.

Haynes, R.J., Tregurtha, R.J., 1998. Effects of increasing periods under intensive arable vegetable production on biological and chemical and physical indices of soil quality. Biology and Fertility of Soils 28, 259–266.

Haynes, R.J., Williams, P.H., 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Advances in Agronomy 49, 119–199.

Haynes, R.J., Swift, R.S., Stephen, R.C., 1991. Influence of mixed cropping rotations (pasture–arable) on organic matter content, water stable aggregation and clod porosity in a group of soils. Soil and Tillage Research 19, 77–87.

John, M.J., 1970. Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. Soil Science 109, 214–220.

Kear, B.S., Gibbs, H.S., Miller, R.B., 1967. Soils of the Downs and Plains Canterbury and North Otago, New Zealand. New Zealand Soil Bureau Report 14. Government Printer, Wellington.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L. (Ed.), Methods of Soil Analysis, Part 2. Soil Science Society of America, Madison, pp. 403–430.

Powlson, D.S., Brookes, P.C., Christensen, B.T., 1987. Measurement of soil microbial biomass provides an early indication of changes in total organic matter due to straw incorporation. Soil Biology & Biochemistry 19, 159–164.

Qualls, R.G., Haines, B.L., 1992. Biodegradability of dissolved organic matter in forest throughfall, soil solution, and stream water. Soil Science Society of America 56, 578–586.

Sparling, G.P., 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. Australian Journal of Soil Science 30, 192–207.

Sparling, G.P., Ross, D.J., 1988. Microbial contributions to the increased nitrogen mineralization after air-drying of soils. Plant and Soil 105, 163–167.

Sparling, G.P., Speir, T.W., Whale, K.N., 1986. Changes in microbial biomass C, ATP content, soil phospho-monoesterase and phospho-diesterase activity following air-drying of soils. Soil Biology & Biochemistry 18, 363–370.

Sparling, G.P., Whale, K.N., Ramsay, A.J., 1985. Quantifying the contribution from the soil microbial biomass to the extractable P levels of fresh and air-dried soils. Australian Journal of Soil Research 23, 613–621.

Stevenson, F.J., 1994. Humus Chemistry. Genesis, Composition, Reactions. Wiley, New York.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring microbial biomass C. Soil Biology & Biochemistry 19, 703–707.

West, A.W., Sparling, G.P., Feltham, C.W., Reynolds, J., 1992. Microbial activity and survival in soils dried at different rates. Australian Journal of Soil Research 30, 209–222.