

Long-term Trends in Fertility of Soils under Continuous Cultivation and Cereal Cropping in Southern Queensland. IV* Loss of Organic Carbon from Different Density Functions

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Abstract

Six southern Queensland soils used for cereal cropping for cultivation periods ranging from 20 to 70 years were subjected to density fractionation. The soils were separated into fractions with densities of <2 , $2.0-2.2$, $2.2-2.4$ and >2.4 Mg m^{-3} using bromoform-ethanol mixture. The <2 Mg m^{-3} fraction (light fraction) contained only 1.8-3.2% of the total soil weight, but accounted for 15-32% of total soil organic C. In five clay soils the rate of loss of organic C from the light fraction was 2-11 times greater than that from the heavy fraction (>2 Mg m^{-3}). The higher the clay content the larger was the difference between these two fractions in rate of loss of organic C. It is inferred that the heavy fraction was closely associated with clay in these soils. In a sandy soil, rate of loss of organic C from the heavy fraction was similar to that from the whole soil.

Introduction

Cultivation of southern Queensland soils for continuous cereal cropping for periods of 20-70 years has led to substantial loss in organic matter from the top (0-0.1 m) layer (Dalal and Mayer 1986b).

The kinetics of loss of organic C associated with different particle size fractions showed that, although the sand-size (0.02-2 mm) organic C fraction was rapidly lost upon cultivation, substantial losses of silt-size (2-20 μm) and clay-size (<2 μm) C fractions also occurred in the initial years, at least in some soils (Dalal and Mayer 1986c). It is likely that this rapidly decomposable portion of soil organic C in all three particle-size fractions constitutes the 'labile' component of soil organic matter which may supply much of the N required by crops. Labile organic matter probably contains plant residues and faunal debris in the sand-size fraction, and also microbial debris and microbial biomass, unassociated or partly associated with silt-size and clay-size mineral particles. This soil fraction is highly enriched in organic C, as compared to the whole soil, and can be separated from the whole soil by densimetric techniques as a light fraction with density of <2 Mg m^{-3} (Greenland and Ford 1964; Ford and Greenland 1968; Satoh and Yamane 1972; Turchenek and Oades 1979; Murayama *et al.* 1979; Sollins *et al.* 1984).

The proportion of light fraction to total organic matter provides an earlier indication of the consequences of different soil managements than the levels of total soil organic matter (Ford and Greenland 1968; Richter *et al.* 1975). However, the rate of loss of soil organic C in the light fraction is rarely studied. Moreover, the effects of soil management and cultural practices on this rate of loss and on the

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amount of light fraction under continuous cereal cropping are not known, although this fraction has been shown to accumulate in arable soils under pasture, and mineralizes relatively rapidly following cultivation (Ford and Greenland 1968). We report here the kinetics of loss of soil organic C in the light fraction. Effects of soil type and cultural practices on rate of loss of the light fraction after long periods (20–70 years) of continuous cropping in six major soils of southern Queensland are also reported.

Materials and Methods

The study area, soil management and cultural practices, soil sampling and analytical procedures are described by Dalal and Mayer (1986a, 1986b).

Density Fractionation Procedure

Densimetric fractionation of soil was done in a bromoform–ethanol mixture following the procedure of Richter *et al.* (1975), modified to include surfactant (Ford *et al.* 1969). To 4 g (oven-dried (105°C) weight) of air-dried soil (<0.25 mm), placed in a 30 ml McCartney bottle, 20 ml of bromoform–ethanol mixture of required density containing 0.02 ml Triton-X (octylphenoxy polyethoxy ethanol) was added and shaken for 1 h on an end-over-end shaker. The suspension was centrifuged at 2 000g for 5 min. The supernatant with the floating and suspended soil particles was poured into a Hirsh funnel fitted with a glass-fibre filter paper (25 mm dia.) and filtered using vacuum. The particles adhering to the bottle were transferred to the filter paper using ethanol. Bromoform was removed by washing with ethanol five times. The separated fraction along with the filter paper was dried at 80°C for 24 h and the weight of the fraction recorded. The <2 Mg m⁻³ fraction is referred to as the 'light fraction'.

Further density-fractionation of soil (fractions obtained were <2, 2.0–2.2, 2.2–2.4 and >2.4 Mg m⁻³) was carried out using the residual soil remaining after removal of the light fraction. The residual soil was washed with ethanol to remove excess bromoform, dried at 80°C for 12–14 h and fractionated as before with higher density bromoform–ethanol mixtures.

The density fractionation of soil was carried out in duplicate at 22 ± 1°C. Only the mean values, calculated on an oven-dry weight basis (105°C), are reported.

Development of the Density Fractionation Procedure

The effects of surfactant concentrations, shaking techniques and soil water contents on the yield of the light fraction (<2 Mg m⁻³) were examined to develop the density fractionation procedure described earlier.

The surfactant, Triton-X, was added to bromoform–ethanol mixtures at 0, 0.05, 0.10 and 0.20% by volume before adjusting the mixture to the required density (<2 Mg m⁻³). The light fraction was obtained using air-dried (25°C) soil following the density fractionation procedure.

The shaking techniques examined were manual shaking (Richter *et al.* 1975), end-over-end shaking for 0.25, 0.5, 1 and 16 h, and ultrasonic treatment (Ford *et al.* 1969) for 5 and 15 min using a Branson B-15 ultrasonic generator (150 W, 20 kHz) operating at 80% capacity. The temperature of the soil–liquid mixture during the ultrasonic treatment was regulated by immersing the container in a constant-temperature (22°C) water-bath. Except for shaking, the fractionation procedure described earlier was used to obtain the light fraction.

The effects of soil water content on the yield of light fraction were studied by using soil dried at 80°C (Ford *et al.* 1969) for 16 h, soil dried at 25°C and soil wetted to –1500 kPa (wilting point) and –10 kPa (field capacity). The respective gravimetric water contents of Waco soil, for example, were 2, 10, 32 and 65% (Table 1). The light fractions were obtained by following the density fractionation procedure of soil samples of mass equivalent to 4 g oven-dried (105°C) weight.

Determination of Organic C

Organic C in each separated fraction was determined by the Walkley and Black method adapted for spectrophotometric determination (Sims and Haby 1975).

Results

Development of the Density Fractionation Procedure

The effects of surfactant, shaking techniques and moisture content on the yield of light fraction ($<2 \text{ Mg m}^{-3}$) and its organic C content and organic C yield are reported in Table 1 for the Waco soil containing 72% clay. Similar trends were observed for the other soils, though these were more variable and of lesser magnitude.

The addition of surfactant, Triton-X (octylphenoxy polyethoxy ethanol) at 0.1% concentration gave maximum yields of light fraction, in both virgin and cultivated soils; the respective increases over the control in the yield of light fraction upon the addition of surfactant (0.1%) were due to a greater extraction of this fraction from soil, since its organic C content remained essentially unaffected by

Table 1. Effect of surfactant, shaking and soil moisture on the amount of light fraction (Lf, $<2 \text{ Mg m}^{-3}$) and its organic C content obtained from virgin and cultivated Waco soils

Treatment	Quantity (and time)	Virgin (1.7% C)			Cultivated (1.0% C)		
		Lf yield (g/100g soil)	Lf C (%)	C yield (g/100g soil)	Lf yield (g/100g soil)	Lf C (%)	C yield (g/100g soil)
Surfactant	0 (% v/v)	2.88	8.90	0.26	0.95	5.83	0.05
	0.05	3.18	8.98	0.28	1.42	5.88	0.08
	0.10	3.42	8.86	0.30	1.62	5.55	0.09
	0.20	2.20	9.96	0.22	0.90	5.23	0.05
Shaking	Manual	3.35	8.10	0.27	1.30	5.13	0.07
	Shaker (0.25 h)	3.32	8.38	0.28	1.32	5.31	0.07
	Shaker (0.5 h)	3.40	8.72	0.30	1.40	5.44	0.08
	Shaker (1 h)	3.42	8.86	0.30	1.62	5.55	0.09
	Shaker (16 h)	4.85	6.82	0.33	1.84	5.05	0.09
	Ultrasonic (5 min)	5.32	5.56	0.30	3.52	2.24	0.08
	Ultrasonic (15 min)	13.00	2.33	0.30	6.28	1.62	0.10
Moisture	2 (% w/w)	3.25	8.38	0.27			
	10	3.42	8.86	0.30		ND ^A	
	32	3.40	6.85	0.23			
	65	80.20 ^B	1.98	1.59			

^A Not determined.

^B Bromoform separated from ethanol.

the addition of surfactant up to 0.1% concentration. At the highest concentration of the surfactant (0.2%), however, the yield of light fraction decreased, possibly owing to flocculation and subsequent precipitation of the suspended light fraction material.

End-over-end shaking of soil-liquid suspension generally gave slightly higher yields of light fraction and also higher organic C contents than manual shaking. Although ultrasonic treatment gave higher yields of light fraction, the organic C content of this fraction was substantially lower than that obtained either by manual or end-over-end shaking. The light fraction obtained from end-over-end shaking of a soil-liquid suspension for 1 h had maximum organic C content in both virgin and cultivated soils.

Air-dried (25°C) or oven-dried (80°C) soil samples yielded light fractions of similar amounts and organic C contents (Table 1). The moisture contents of air-dried samples were, approximately, 10% in Waco soil, 5% in Langlands-Logie, Cecilvale, Billa Billa and Thallon soils and 1% in Riverview soil. These moisture contents were unlikely to affect the yield of the light fraction (Table 1). Soil samples moistened to field capacity, however, cannot be used because of the formation of separate ethanol-water and bromoform layers.

Table 2. Distribution of top (0-0.1 m depth) soil from virgin sites in different density fractions

Soil series (No. of sites)	Soil weight distribution in density fractions (g 100g ⁻¹ soil)			
	<2	2.0-2.2	2.2-2.4	>2.4 Mg m ⁻³
Waco (5)	2.6	81.3	12.5	3.8
Langlands-Logie (6)	2.8	9.0	65.2	23.0
Cecilvale (7)	2.2	16.8	31.5	49.5
Billa Billa (7)	3.2	5.5	48.2	43.2
Thallon (6)	1.8	ND	0.5 ^A	97.8
Riverview (5)	2.4	ND	3.1 ^A	94.6

^A 2.0-2.4 Mg m⁻³ fraction.

Density Fractionation of Soil, and Organic C Contents of Fractions

Distribution of soil weight among the various fractions differed markedly. Waco soil (with predominantly montmorillonitic clay) was mostly in the 2.0-2.2 Mg m⁻³ fraction, Thallon and Riverview soils (kaolinitic) mostly in >2.4 Mg m⁻³, and Langlands-Logie, Cecilvale and Billa Billa (randomly interstratified clay minerals) mostly in 2.2-2.4 and >2.4 Mg m⁻³ density fractions (Table 2).

Table 3. Organic C contents of different density fractions of top (0-0.1 m depth) soil from virgin sites

Soil series (No. of sites)	Soil	Organic C content (%)				Total org. C recovery (%)
		<2.0	2.0-2.2	2.2-2.4	>2.4 Mg m ⁻³	
Waco (5)	1.63	12.8	1.46	1.33	0.45	104
Langlands-Logie (6)	2.23	20.5	3.85	1.59	0.70	96
Cecilvale (7)	1.73	16.3	4.2	1.32	0.42	98
Billa Billa (7)	1.48	15.5	6.9	1.17	0.32	107
Thallon (6)	0.77	7.3	ND	0.79 ^A	0.65	100
Riverview (5)	1.28	15.6	ND	0.93 ^A	0.90	98

^A 2.0-2.4 Mg m⁻³ fraction.

In all soils, the light fraction (<2 Mg m⁻³) was highly enriched in organic C relative to the whole soil (Table 3). Only in some soils was the 2.0-2.2 Mg m⁻³ fraction enriched in organic C and the heavier fractions (>2.4 Mg m⁻³) had less organic C than the whole soil. Overall total organic C recovery from all fractions was satisfactory (96-107%).

As a proportion of the total soil's weight, the light fraction was small (1.8-3.3 g 100 g⁻¹ soil), although it contained as much as 34% of total soil organic C (e.g.

for the Billa Billa soil). With respect to organic C distribution, therefore, these soils may usefully be fractionated into two components, a light fraction ($<2 \text{ Mg m}^{-3}$) rich in organic C and a heavy fraction ($>2 \text{ Mg m}^{-3}$) of low organic C concentration. In some soils (e.g. Langlands-Logie, Cecilvale and Billa Billa), however, the $2.0\text{--}2.2 \text{ Mg m}^{-3}$ fraction could be considered with the light fraction.

Kinetics of Organic C Loss from the Light Fraction ($<2 \text{ Mg m}^{-3}$)

The loss of light fraction organic C from six soils in relation to period of cultivation is shown in Fig. 1. This relationship was satisfactorily expressed by a first-order rate equation, similar to that described by Dalal and Mayer (1986b) for total soil organic C. The equation is,

$$C_t = C_e + (C_o - C_e)\exp(-k_{Lf}t),$$

where C_o , C_e and C_t are the amounts of organic C ($\text{t C ha}^{-1} 0.1 \text{ m}^{-1}$), in the light fraction initially, at equilibrium, and at time t years, and k_{Lf} (year^{-1}) is the rate of organic C loss from the light fraction. The kinetic parameters of organic C loss from the light fraction are given in Table 4.

Rates of organic C loss from the light fraction (k_{Lf}) varied from 0.12 year^{-1} (Thallon) to 0.83 year^{-1} (Riverview). The higher the k_{Lf} value, the faster the light fraction organic C reaches equilibrium. The k_{Lf} values were significantly related to the reciprocal of the clay content ($r=0.87^{**}$) and frequency of stubble retention ($r=0.82^*$) for all six soil series.

The C_o and C_e values were lowest in Thallon soil. In Langlands-Logie, Cecilvale and Thallon soils, 80–95% of organic C from the light fraction would be lost at equilibrium $[(C_o - C_e)/C_o]$. The C_o values of all soil series were significantly correlated with total potassium in the soil ($r=0.82^*$), and this probably reflects the effect of clay mineralogy on the amount of light fraction organic C accumulated initially. The C_e values were significantly correlated with aggregation index ($r=0.86^*$) and clay content ($r=0.83^*$), reflecting thereby the protective effect of soil clay.

Kinetics of Organic C Loss from the Heavy Fraction

The kinetic parameters of loss of heavy fraction ($>2 \text{ Mg m}^{-3}$) organic C, calculated according to the first-order rate process, are given in Table 5.

The rate of loss of heavy fraction organic C, k_{Hf} varied from 0.026 year^{-1} (Langlands-Logie) to 1.494 year^{-1} (Riverview). In all soils, except Riverview, k_{Lf} exceeded k_{Hf} with k_{Lf}/k_{Hf} ranging from 2 to 11. This suggests that it is possible to separate soil organic C into at least two fractions that differ in their kinetics and possibly in their other biological, chemical and physical characteristics.

For all soils, k_{Hf} was significantly correlated with the reciprocal of clay content ($r=0.93^{**}$), organic C/urease activity ($r=0.99^{**}$), bulk density ($r=0.90^*$) and frequency of stubble retention ($r=-0.88^*$).

Except for Langlands-Logie soil, less than 45% of organic C from the heavy fraction would be lost at equilibrium compared with 80–85% from the light fraction. The C_o and C_e values of the heavy fraction were related to mean annual rainfall ($r=0.8$, $P < 0.1$) and dispersion ratio ($r=-0.8$, $P < 0.1$), respectively.

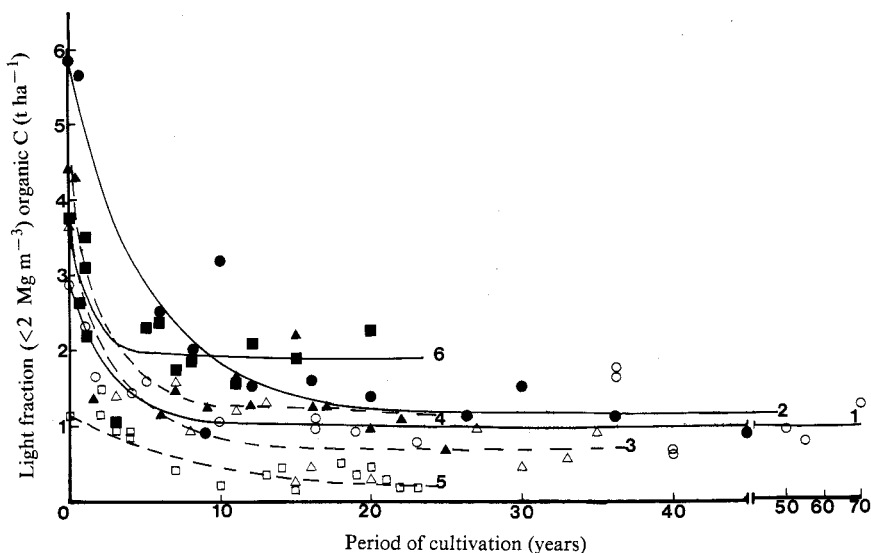


Fig. 1. Relationship between light fraction organic C and period of cultivation. 1, ○ Waco; 2, ● Langlands-Logie; 3, △ Cecilvale; 4, ▲ Billa Billa; 5, □ Thallon; 6, ■ Riverview.

Table 4. Kinetic parameters of organic C loss from the light fraction of six soils

Soil series (No. of sites)	C_o (t C ha ⁻¹ 0.1 m ⁻¹) ^A	C_e	k_{L_f} (year ⁻¹)	r^B
Waco (21)	2.86	1.00	0.365	0.93
Langlands-Logie (18)	5.88	1.20	0.194	0.91
Cecilvale (19)	3.63	0.69	0.293	0.96
Billa Billa (21)	4.43	1.24	0.418	0.94
Thallon (22)	1.19	0.18	0.119	0.82
Riverview (18)	3.75	1.91	0.830	0.83

^A C values were calculated as light fraction organic C (g C 100g⁻¹ soil) × soil weight (ha⁻¹ dm⁻¹) allowing for soil bulk density (Dalal and Mayer 1986b).

^B All r values significant at $P < 0.05$.

Table 5. Kinetic parameters of organic C loss from heavy fraction^A

Soil series	C_o (t ha ⁻¹ dm ⁻¹)	C_e	k_{H_f} (year ⁻¹)	r^B
Waco	11.08	6.56	0.033	0.94
Langlands-Logie	16.22	0.98	0.026	0.96
Cecilvale	13.89	9.47	0.143	0.94
Billa Billa	9.23	6.68	0.110	0.68
Thallon	6.32	3.54	0.036	0.85
Riverview	11.96	7.47	1.494	0.87

^A Organic C_i in the heavy fraction = total soil organic C_t (Dalal and Mayer 1986b) - organic C_l in the light fraction, where t is the period of cultivation (years).

^B Significant at $P < 0.05$.

Discussion

The Density Fractionation Procedure

The effect of the addition of surfactant, Triton-X, on the amount of light fraction agrees with the results of Ford *et al.* (1969) who used sodium dioctyl sulfosuccinate (0.1% by weight). Surfactant added at low concentrations increases the proportion of non-humified material in the light fraction as well as the total amount removed from the soil (Ford *et al.* 1969).

The ultrasonic treatment extracted more light fraction material, but this material contained less organic C content than that produced by shaking, although the yields of organic C obtained by these two methods were essentially similar. The change in temperature of the suspension during the ultrasonic treatment may partly account for these differences. Although care was taken to minimize temperature changes by immersing the reacting vessel in a water-bath, ultrasonic treatment did raise the temperature of the suspension (2–3°C in 5 min to about 5°C in 15 min), resulting in considerably greater soil dispersion and changing solution density.

The effects of moisture on the amounts of light fraction extracted from these soils are similar to those observed by Ford *et al.* (1969). However, with the bromoform-ethanol mixtures, an air-dried rather than oven-dried (80°C) soil sample can be used (Richter *et al.* 1975), for separating the light fraction. It is not known whether the air-dried samples can be used for further fractionation ($> 2 \text{ Mg m}^{-3}$), since oven-dried (80°C) samples were used for this purpose.

The Soil Density Distribution

The densimetric fractionation of these six soils showed generally similar distributions to those reported by Satoh and Yamane (1972) and Turchenek and Oades (1979); the coarse-textured soils (Riverview; 18% clay) had larger separates at high densities than the fine-textured soils (Waco, 72% clay) (Table 2). However, clay mineralogy also appears to affect the distribution. For example, Thallon soil, containing 59% clay, had a similar density-distribution to that of Riverview soil (Table 2), with both soils having a predominantly kaolinitic clay (Dalal and Mayer 1986a).

Heavy liquid fractionation of clay minerals follows a similar density trend (Halma 1969). This density fractionation concept may also provide a relative erodibility index of soils. For example, a soil having most of its weight in $< 2.4 \text{ Mg m}^{-3}$ (Waco, Cecilvale, Langlands-Logie and Billa Billa) would be more erosive than a soil with most weight in $> 2.4 \text{ Mg m}^{-3}$ fraction (Thallon, Riverview). This concept, however, needs to be further examined.

Density Distribution of Soil Organic C

The light fraction ($< 2 \text{ Mg m}^{-3}$) accounted for 17–34% of total organic C in these six soils. Ford *et al.* (1969) obtained similar results for a number of Australian soils. In some soils, the $2.0\text{--}2.2 \text{ Mg m}^{-3}$ fraction is enriched in organic C (Table 3), and so may contribute to the labile organic matter (Ford and Greenland 1968). These fractions contain most of the partly decomposed plant residues, microfloral and faunal debris and most of the microbial biomass (Oades and Ladd 1977).

Kinetics of Organic C Loss from the Light and Heavy Fractions

Loss of organic C from the light fraction (k_{Lf}) was 2–11 times faster than that from the heavy fraction (k_{Hf}) in the fine-textured soils (34–72% clay) but slower

in the coarse-textured Riverview soil (18% clay). Rates of total organic C loss in these soils have been associated with soil characteristics (e.g., clay content, organic C/urease activity, aggregation index and exchangeable sodium percentage) that indicate relative inaccessibility or protection of organic matter against microorganisms and proteolytic and degradative enzymes (Dalal and Mayer 1986b). The coarse-textured soil, therefore, may provide less protection even for the organic C apparently associated with the inorganic minerals (heavy fraction). In fact, in Riverview soil, the k_{Hf} value (1.49 ± 0.35) was similar to that of the whole soil (1.24 ± 0.34).

In clay soils, however, organic C in the heavy fraction is afforded greater protection than that in the light fraction. The $k_{\text{Lf}}/k_{\text{Hf}}$ ratio generally increased with the clay content, indicating a clearer separation between the relatively accessible light fraction and relatively protected heavy fraction organic matter. Corroboration of these results was provided by carbon-13 nuclear magnetic resonance spectroscopic studies of organic C fractions from Langlands-Logie soil (Skjemstad, J. O., Dalal, R. C., and Barron, P. F., unpublished data) and organic C dynamics in particle-size fractions under cultivation (Dalal and Mayer 1986c). These studies showed that, although the chemical nature of organic matter in different size fractions remained essentially unchanged, the relative amounts of clay-size organic matter increased with the period of cultivation.

The closer relationship between the reciprocal of the clay content and k_{Hf} than that with k_{Lf} suggests again that the heavy fraction is more closely associated with, and better protected by, clay than the light fraction. Richter *et al.* (1975) also observed a close correlation between the clay content and organic C in the 2.0–2.3 Mg m^{-3} density fraction. The significant relationship between both k_{Lf} and k_{Hf} and frequency of stubble retention suggests the contribution of crop residues to both light and heavy fraction organic C.

This study shows that, in the soils considered, organic matter can be separated into a relatively more labile, light fraction ($< 2 \text{ Mg m}^{-3}$), probably consisting of plant residues, microfloral and faunal debris and microbial biomass, and a less labile, heavy fraction ($> 2 \text{ Mg m}^{-3}$) mainly associated with the clay. However, the distribution of these two fractions within the soil matrix, and their relative significance to nutrient supply (e.g. nitrogen) to crops is not clear. Young and Spycher (1979) proposed that light fraction materials are located at the surface of aggregates and are, therefore, easily accessible to the soil organisms which are confined to aggregate surfaces and extra-aggregate space. The heavy fraction materials, however, are contained in intra-aggregate regions and thus protected from soil organisms. The light fraction organic matter should, therefore, be relatively more readily mineralized than the heavy fraction. Ford and Greenland (1968) showed that when soils under pasture were cultivated, the net losses of light fraction (2 Mg m^{-3}) N due to mineralization were 25–60%, although this fraction accounted for only 7–23% of the total soil N. However, Sollins *et al.* (1984) found greater net N mineralization from the heavy fraction ($> 1.6 \text{ Mg m}^{-3}$) because their heavy fraction also contained most of the microbial biomass which occurs mostly in 1.6–2.0 Mg m^{-3} density fraction (Turchenek and Oades 1979). The N dynamics in both light and heavy fractions from these soils subjected to different periods of cultivation (20–70 years) will be subsequently reported.

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