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Decomposition of Organic Matter in Soil as Influenced by Texture and Pore Size Distribution

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Abstract

The carbon mineralization of fresh organic matter in soils of different texture was determined using ^{14}C-labelled tobacco (*Nicotiana tobacum*) starch solution and ^{14}C-labelled barley (*Hordeum vulgare)* straw particles. A heavy clay soil (56% illite clay) was mixed with acid washed sand to come up with a range of different soil textures, with clay contents varying between 5.6 and 56%. For each resultant texture, three treatments were imposed, namely, barley straw amendment, tobacco starch solution amendment and an unamended control. Total porosity ranged from 60.3% in soils with 56% clay content to 43.7% in soils with a clay content of 5.6%. Total clay content, porosity, bulk density and pore-volume (0.75 to 6 m in diameters) were all positively correlated to $^{14}CO_2$-C evolution (a measure of decomposition) of the amended soils. In both amended and unamended soils, the C mineralization decreased with increasing clay content, with ranges of 42-121 mg C g^{-1} soil with 5.6% clay and 34-107 mg C g^{-1} soil with 56% clay. Regression analysis showed that pores <75 m in diameter had the greatest influence on the amounts of CO_2-C released (R^2 =0.91 for starch and 0.94 for straw). Our findings provide empirical evidence to support the theory that decomposition of fresh organic matter is governed by its physical accessibility by microbes as determined by soil texture and pore size distribution. We concluded that pores of <75 μm are responsible for the protection of organic substrates against microbial decomposition in soils. The study provides insights on the role of clays in organic matter stabilization and hence the vulnerability of the limited amounts of organic inputs often available to smallholder farmers in tropical environments where soils are predominantly low in clay.

Key words: organic substrate, carbon mineralization, soil texture, pore size distribution, organic matter decomposition

Introduction

The influence of soil texture on organic matter decomposition has been widely studied and results indicate that the rate of decomposition and net mineralization depend on the accessibility of organic substrates to soil organisms (Oades, 1984; Christensen, 1987; Amato and Ladd, 1992, Hassink, 1996). Although organic matter decomposition studies are numerous, few have addressed the relative importance of direct and indirect mechanisms of soil texture control on organic matter stabilization (Srensen, 1981; van Veen *et al.*, 1985). In general, the quantity and nature of the soil clay affect the amount of C stabilized in soil. Fine textured soils (clays) often contain higher amounts of organic matter than sandy soils. Two mechanisms have beet put forward to explain the effect of soil texture on organic matter decomposition:

- the protective action by clays against organic matter degradation through the formation of complexes between metal ions associated with large clay surfaces and high CEC (Giller *et al.*, 1997); and
- accessibility by soil microbes (van Veen and Kuikman, 1990).

Clay particles are believed to protect some of the more easily decomposable organic compounds from rapid microbial breakdown through encrustation and entrapment (Paul and van Veen, 1978; Anderson, 1979; Tisdall and Oades, 1982).

The soil pore size distribution is one factor determining the microbial habitat since it is assumed that microorganisms mainly live in pores of a certain size. Considering the size of bacterial cells, pores of a neck diameter of 2-6 μm are favourable microhabitats for soil bacteria (Hattori and Hattori, 1976). Hassink (1992) also found a good correlation between the habitable pore size fraction and N mineralization. Killham *et al*. (1993) showed that substrate utilization by microbes in soil was strongly affected by its location, both in terms of pore size and the matric water potential under which turnover takes place. It should, however, be noted that only a very small fraction of organic material in soil is likely to be at close proximity to soil organisms at any one time (Adu and Oades, 1978).

Organic matter may be physically protected in soil such that large amounts of decomposable compounds can be found in the vicinity of starving microbial populations (van Veen and Kuikman, 1990). Elliott *et al*. (1980) used a combination of bacteria, amoebae and nematodes to demonstrate the importance of microbial trophic structure in relation to soil texture and habitable pore space. Ladd *et al*. (1985) found a significant linear relationship between residual labelled C in topsoil and clay contents ranging from 5 to 42%. The higher the clay content in the different soils, the higher the residual C content after 8 years of experimentation. On the assumption that bacterial cells were found in pores with a diameter of between 0.8 and 6 μm (Kilbertus, 1980; Hattori and Hattori, 1976), the aim of the experiment was to test how soil texture and habitable pore space affect decomposition of fresh organic matter applied to soil.

Materials and Methods

Soil-sand mixtures

The topsoil of a heavy clay from a site in Uppsala, Kungsängen soil, classified as a fine, illitic, frigid *Gleyic Cambisol* in the FAO-system (Kirchmann, 1991) was used. The same amount of air-dried soil comprising of 56% clay (<0.002 mm), 39.9% silt (0.002-0.06 mm) and 4.1 % sand (0.06-2 mm) and with a pH of 6.9, 2.14% C and 0.26% N, was mixed with different quantities of acid-washed quartz sand (0.3-0.5 mm) to create a range of textures resulting in different soil pore-size distribution. As the same amount of soil was mixed with increasing proportions of sand, it was assumed that the soil mixtures under investigation were uniform with respect to:

a) the number of exchange sites which was the same in all the mixtures,
b) the initial amount of organic matter, and
c) the initial number of microbes present.

The only physical aspect that was changed was the pore size in the soil-sand mixtures. Bulk densities and volumetric water contents of the mixtures were determined at -500 KPa, -1 500 KPa wilting point) and -4 000 KPa water pressures (Table 19.1). The pore size distribution of each soil mixture was obtained from the moisture characteristic curves relating volumetric water content to soil metric potential. The porosity of the soil-sand mixtures was determined assuming a particle density of the sand of 2.65 g cm^{-3} and for the Kungsängen soil, of 2.62 g cm^{-3} (Kirchmann, 1991).

Table 19.1: Particle size distribution, bulk density and soil pore space of the different soil treatments

10g Kungssangen soil+ *x*g sand	Soil texture(%)			Bulk density Mgm^{-3}			Total Porosity		
mixtures	Sand	Silt	Clay	Control soil only	soil+ starch	soil+ straw	Control soil only	soil+ starch	soil+ straw
0.0	4.1	39.9	56.0	1.1	1.1	1.0	60.4	60.4	62.6
2.5	23.3	31.9	44.8	1.2	1.2	1.1	56.0	56.0	58.5
6.7	42.5	23.9	33.6	1.3	1.3	1.2	51.3	51.3	54.7
10.0	52.0	20.0	28.0	1.3	1.3	1.2	50.2	50.2	53.6
15.0	61.6	16.0	22.4	1.4	1.4	1.3	48.8	48.8	49.8
23.3	71.2	12.0	16.8	1.4	1.4	1.4	46.9	46.9	47.7
40.0	80.8	8.0	11.2	1.4	1.4	1.4	45.1	45.1	45.5
90.0	90.4	4.0	5.6	1.5	1.5	1.5	43.3	43.3	43.3

Soil amendments

Triplicate samples of each clay content (10 g of Kungsängen soil plus sand as described in Table 19.1), were moistened to 45% of their respective water-holding capacities. The samples were then amended with either 2 ml of a tobacco (*Nicotiana tobacum*) starch solution containing 44.4 mg starch C, 45.5 μCig^{-1} starch ^{14}C or 2 ml distilled water plus 100 mg ground (<2 mm) barley straw (*Hordeum vulgare)* containing 100 $\mu Cig^{-1}C$ plant ^{14}C and 2.1 mg plant N. The moistened soil treatments were incubated at 25°C for 45 days. Incubation vials of corresponding moistened soil-sand mixtures without organic amendments were used as controls. Determination of CO_2 evolution was done using 10 ml traps with 0.1 M NaOH (Stotzky, 1965), that were titrated with 0.1 M HCl after 1, 3, 7, 11, 17, 24, 31, 38 and 45 days. Radioactivity of absorbed $^{14}CO_2$ was determined by scintillation counting (Beckman liquid scintillation systems LS 1801) and residual organic ^{14}C was determined by wet combustion of the oven dried soil subsamples.

Statistical Analyses

Data were subjected to a two-factor (time and treatment) analysis of variance (ANOVA) to determine if the materials mineralized differently with time. Possible mean differences of the cumulative mineralization data were tested using independent Student t-tests and residual ^{14}C was correlated to the different soil properties using linear regression analysis with the statistical package of MINITAB (Ryan *et al.*, 1985).

Results

Changes in soil pore size distribution upon amendments

Changing the texture through sand amendments increased the bulk densities of the soil but lowered the total soil porosity (Table 19.1). The addition of tobacco starch solution to the soils did not alter the physical structure of the soils resulting in these soils having the properties similar to the control soils. Bulk densities ranged from 1.05 Mg m^{-3} (soil 56% clay) to 1.50 Mg m^{-3} (soil 5.6% clay) in control and starch-amended soils. However, adding straw particles (*Hordeum vulgare*) to the same soils lowered the bulk densities in high clay soils but not in more sandier soils which had almost equal bulk densities to control soils. Total porosity increased with increasing clay content from 43.3 to 60.4% in the soil-sand mixtures and from 43.3 to 62.6% in the straw-amended soil-sand mixtures.

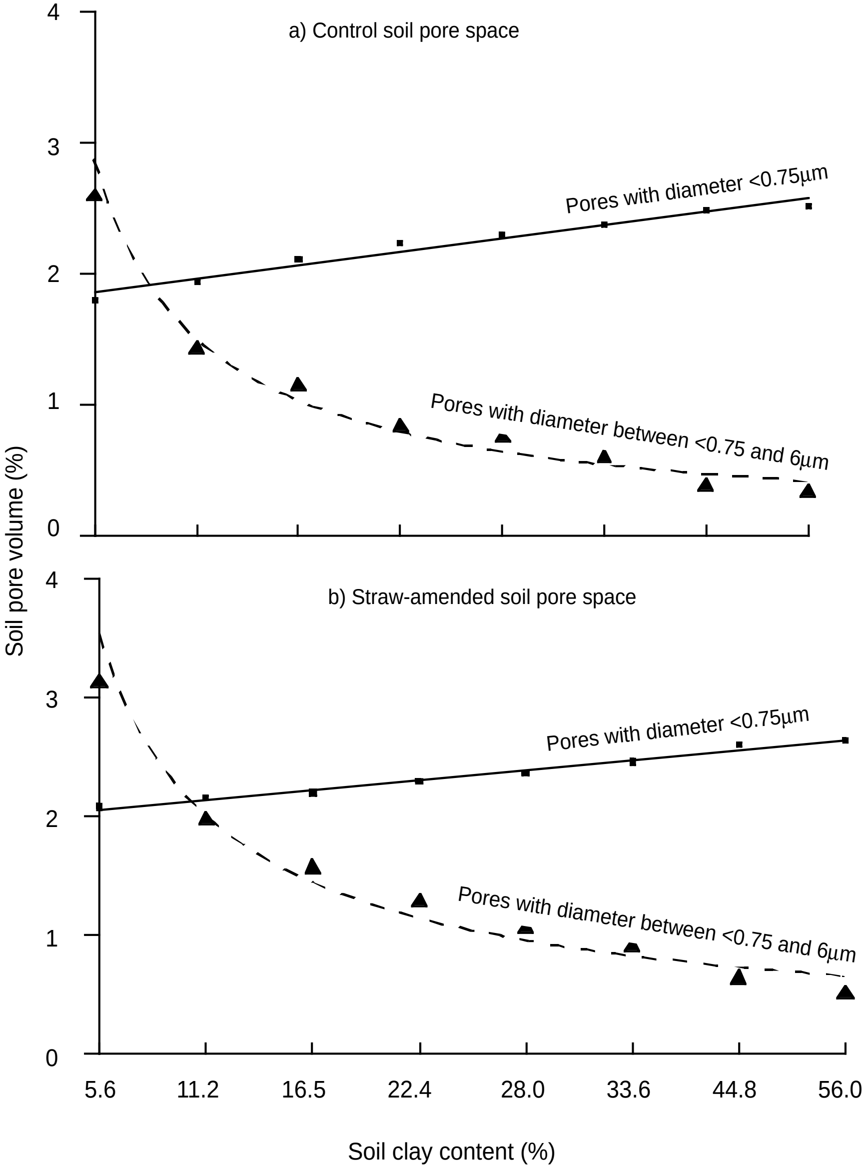
The absolute pore volume in the soil-sand mixtures was affected when sand was added with increasing quantities to the Kungsängen soil (Table 19.2). The volume of pores with diameters of <6 m was higher in straw amended soils than in starch amendments and the control soil-sand mixtures. Differences were statistically significant only in soil-sand mixtures of between 5.6 and 28% clay content ($P<0.05$) while in all the high clay soils (>28% clay), the volume of pores <6 µm occupied between 44 to 50% of total porosity (Table 19.2). Soil pore volumes of diameters between 0.75 and 6 µm in both straw and starch amended soils decreased exponentially with increasing clay content. In the same soils, the pore volume of the smaller, supposedly inaccessible pores of <0.75 m in diameter increased linearly and showed significant relationships (R^2 = 0.91 for starch amended and 0.94 for straw amended soils.

Table 19.2: Soil pore space, pore volume and CO_2-C evolution in amended and unamended soils

Soil treatment and pore size	56.0% clay	44.8% clay	33.6% clay	28.0% clay	22.4% clay	16.8% clay	11.2% clay	5.6% clay
Control soil								
Pores >6 µm (%)*	50	52	55	60	66	71	78	85
Pores >6 µm (mL)	3	3	4	5	6	8	12	24
Pores <0.75 µm (%)*	44	41	36	30	25	19	12	6
Pores <0.75 µm (mL)	3	2	2	2	2	2	2	2
Pores (0.75-6) µm (%)*	6	6	9	10	9	10	9	9
Pores (0.75-6) µm (mL)	0.4	0.4	0.6	0.8	0.8	1	1	3
CO2-C evolution (mg C g^{-1} soil)	29	31	35	35	36	37	38	40
Tobacco starch- amended soil								
Pores >6 µm (%)*	50	52	55	60	66	71	78	85
Pores >6 µm (mL)	3	3	4	5	6	8	12	24
Pores <0.75 µm (%)*	44	41	36	30	25	19	12	6
Pores <0.75 µm (mL)	3	2	2	2	2	2	2	2
Pores (0.75-6) µm (%)*	6	6	9	10	9	10	9	9
Pores (0.75-6) µm (mL)	0.4	0.4	0.6	0.8	0.8	1	1	3
CO2-C evolution (mg C g^{-1} soil)	10.3	114	120	121	118	120	127	141
Barley straw-amended soil								
Pores >6 µm (%)*	51	52	56	61	62	67	74	82
Pores >6 µm (mL)	3	3	4	5	6	8	12	24
Pores <0.75 µm (%)*	41	39	32	27	24	19	14	7
Pores <0.75 µm (mL)	3	3	2	3	2	2	2	2
Pores (0.75-6) µm (%)*	8	10	12	12	14	14	13	11
Pores (0.75-6) µm (mL)	0.5	0.6	0.9	1	1	2	2	3
14CO2-C evolution (mg C g^{-1} soil)	97	103	108	100	101	103	110	118

*expressed as a percentage of total porosity

Figure 19.1: The relationship between soil-pore volume and clay content of (a) unamended control soil and (b) the same soils following addition of barley straw



Carbon Dioxide Evolution

In the control soil-sand mixtures, there was very little difference in the amount of native soil organic matter evolved as CO_2 after 45 days of incubation. Significant differences were apparent at high clay contents ($P<0.05$). Total cumulative values ranged from 29.3 mg C g^{-1} soil (56% clay) to 40.1 mg C g^{-1} soil (5.6% clay). The same trend of C mineralization was observed when soils were amended with fresh organic matter (Table 19.2). Both barley straw and starch were decomposed to a higher extent in soils with low clay contents of 5.6 to 16.8%. The CO_2 evolution from starch amended treatments was greater than from straw amended ones. At the end of the incubation period, more than quarter of the added C had been mineralized in all the treatments. Cumulative CO_2-C evolution data from starch-amended soils showed differences between high and low clay content within one week and these differences became statistically significant from the third week onwards ($P<0.05$) (Figure 19.2a).

In the straw-amended soils, there was very little difference in the evolution of $^{14}CO_2$-C in six of the eight mixtures ($P>0.05$) (Figure 19.2b). The pattern of C mineralization observed was very similar to that of the control soil-sand mixtures. Cumulative $^{14}CO_2$-C evolution data showed that C mineralization was initially rapid and after about 3 weeks, decreased rates of $^{14}CO_2$-C production following a first-order function were observed. At the end of the incubation period, the highest percentage of labelled C evolved (39.1% of added straw ^{14}C) was noted in soil with 5.6% clay, the other 7 soil mixtures released between 29.2 and 36.5% of the C added.

Relationships between C mineralization and soil physical properties

There were good correlations between labelled substrate C mineralization and clay content, bulk density and soil pore spaces. Bulk density was positively related to C mineralization whereas total porosity was negatively related (Table 19.3). Differentiating soil pore diameters into three possible groups (<0.75 m, 0.75-6 m and >6 m), the highest correlation with C evolution was obtained with the volume of pores of diameters <0.75 m ($R^2 = 0.914$ for starch and 0.935 for straw; $p < 0.001$) (Figure 19.3). The results showed that the higher the concentration of these small pores, the less the $^{14}CO_2$-C evolved. Linear regression analysis showed that translating percentage porosity into absolute pore volume per given soil did not improve correlations between the different pore groups and $^{14}CO_2$-C evolution.

Figure 19.2: Net cumulative $^{14}CO_2$-C evolution of soil-sand mixtures amended with a) tobacco starch solution and b) <2mm granulated barley straw. Means are based on n = 3

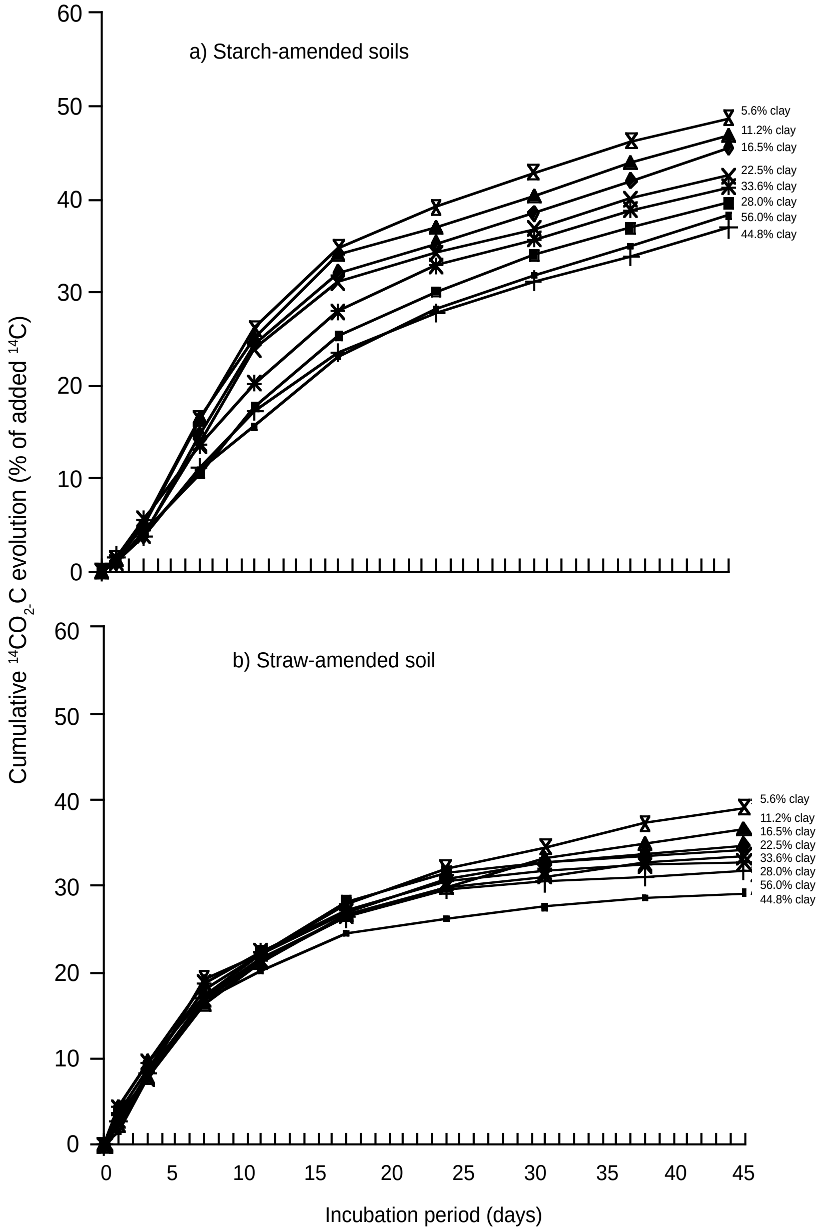
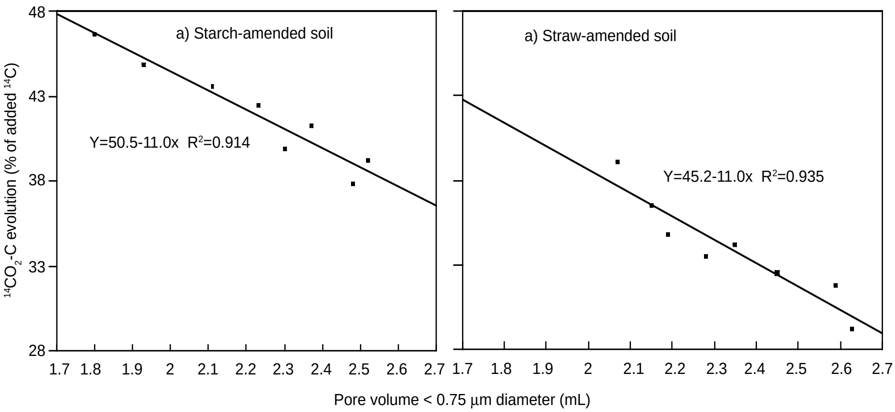


Table 19.3: Linear regressions for $^{14}CO_2$-C mineralization between (a) tobacco (*Nicotiana tobacum*) starch and (b) barley (*Hordeum vulgare*) straw and soil properties after 45 days of soil incubation

Quality variable (x)	Dependent variable (y)	Intercept	Slope	R^2
Clay (%)		46.3	-0.2	0.81
Bulk density		18.1	18.1	0.76**
Total porosity (%)		65.7	-0.5	0.78**
Total pore volume (mL)		38.2	0.3	0.75**
Porosity (<0.75 m) (%)	a	47.6	-0.2	0.91***
Pore volume (<0.75 m) (mL)		50.5	-0.1	0.91***
Porosity (>6 m) (%)		27.1	0.2	0.91***
Pore volume (>6 m) (mL)		39.1	0.4	0.75**
Clay (%)		38.5	0.2	0.91***
Bulk density		13.4	16.2	0.90***
Total porosity (%)		56.2	-0.4	0.90***
Total pore volume (mL)	b	29.8	0.4	0.79**
Porosity (<0.75 m) (%)		40.2	-0.2	0.92***
Pore volume (<0.75 m) (mL)		45.2	-1.1	0.94***
Porosity (>6 m) (%)		17.1	0.6	0.93***
Pore volume (>6 m) (mL)		30.8	0.4	0.79***

*** - significant at $p < 0.001$, ** - significant at $p < 0.01$, * - significant at $p < 0.05$

Figure 19.3: Relationship between cumulative $^{14}CO_2$-C evolution and soil pore volume of diameters of <0.75m for starch-amended soils (a) and straw-amended soils (b)



Discussion

The addition of a readily decomposable organic C sources stimulated the mineralization of native soil organic C in the soil-sand mixtures. The extent to which the two different substrates ^{14}C was decomposed was consistent in both amendments being higher in low clay than in high clay soils. Given that the *Kungsangen* soils used in treatments already had high initial C and N, sampling possibly opened up some labile C that would have been otherwise protected in soil aggregates resulting in increased C evolution. However, the nature of the decomposer population and available pore space have been found to influence the rate of mineralization of organic substrates added to soil (Srensen, 1975; Elliott *et al.*, 1980; Hassink *et al.*, 1993). Pores with diameters of less than 0.75 μm were presumed to be responsible for the protection of microbial decomposition of the fresh organic substrates added to soil-sand mixtures. These pores were found in higher proportions in high clay soils and thus may explain why high clay soils are better able to protect organic matter from decomposition. The concept of microbial accessibility in soil seem to be most meaningful if it is used in relation to the size of the microbial inaccessible pores. The structure of the decomposer community available in the Kungsängen soil was not investigated in this study. In our study, we sampled soils that had been under intensive cereal production for over 25 years (Kirchmann, 1991) thus the amount and quality of native organic matter in the soil was assumed to be similar and was not disturbed during sample preparation. The number of exchange sites of the clay were kept constant and the effect of pore size could be investigated without interaction of other media. Although soil texture has been shown to correlate with long-term C dynamics (Jenkinson, 1971; Ladd *et al.*, 1985), our results show that differences in soil texture in the control soils had no significant effect on CO_2-C mineralization of native soil organic matter. We therefore suggest the key factor controlling organic matter decomposition in different textured soils is the soil pore size and distribution. Since soil texture controls the pore size distribution and it is in this way that conclusions on texture affecting organic matter decomposition have been made (Hassink, 1992; Hassink *et al*, 1993). Our results have shown that as the soils became more sandy, the degree of soil porosity decreased. Carbon dioxide evolution from the two added organic substrates appeared to be strongly affected by the soil pore-size distribution and pore continuity.

There is no general agreement on the critical factors influencing movement of organisms in soil, but larger organisms are probably more restricted than smaller ones. Pore-size distribution and continuity are known to influence soil water availability, gas diffusion and the movement of soil organisms (Coleman *et al.*, 1984; Scott *et al.*, 1996). Pore-neck size determines whether an organism can enter a given pore, thus whether a substrate located within the soil pore is available to microorganisms. We found that the best correlation was the negative relationship between soil pores of less than 0.75 µm and the amount of $^{14}CO_2$-C evolved for both starch- and straw-amended treatments. These results indicate the importance of those pores that are inaccessible for microbes in the stabilization of organic matter. The theory of physical accessibility and its linkage between soil texture as described by soil pore size distribution to decomposition of fresh organic matter was affirmed. Hassink *et al.* (1993) found good relationships between pore volumes of between 0.2 and 1.2 µm diameter and bacterial biomass. The difference between $^{14}CO_2$ released from the high clay soils and the low clay soils in both starch and straw amendments may be considered to be a measure of the proportion of starch or straw in micropores potentially protected from microbial degradation. Adu and Oades (1978) attributed physical protection from microbial decomposition when a portion of soluble starch in micropores was left unmineralized.

The concept of substrate quality has also been identified as an important factor in soil organic matter stabilization (McClaugherty *et al.*, 1985; Duxbury *et al.*, 1989; Melillo *et al.*, 1989). Although the contribution of native soil organic matter to total carbon mineralization was significant as was shown by the control soils, several studies have shown what Jenkinson (1971) described as the 'priming action' following the addition of fresh organic matter to soil. Carbon dioxide evolution from the control (unamended) soils was significantly lower than that of amended soil signifying the stimulation of 'microbial priming action' following soil amendments. Higher mineralization and decomposition rates are known to be stimulated by increased N availability (Palm and Sanchez, 1991; Tian *et al.*, 1995). Our study showed that incubation of starch-amended soils showed greater utilization than high N-containing, thus higher quality barley straw (Cadisch and Giller, 1997). This was probably due to an abundance of readily available C for maximum utilization for microbial growth relative to N. The delayed differences in C mineralization of straw amended soils observed towards the end of the study imply a gradual narrowing of the C:N ratio when at some point, N becomes no longer limiting to microbial growth. In addition, accessible pore space also played a major role during the mineralization of a presumably distributed (soluble starch) organic substrate and more strongly of unevenly distributed one (granulated straw).

Conclusion

Our findings provide a challenge to soil fertility research focussing on soil organic matter build-up and maintenance using organic amendments. Given that most of the smallholder farming areas in tropical environments are dominated by sandy soils, the vulnerability of the limited amounts of organic inputs available in most of these farming systems is implied. The study provides empirical evidence to support the theory that decomposition of fresh organic matter is governed by its physical accessibility by microbes as determined by soil texture and pore size distribution. We therefore concluded that pores of diameters of <75 μm were responsible for the protection of organic substrates against microbial decomposition in soils. To be able to understand fully the importance of clay in organic matter stabilization, there is a need for more research in the soil pore system and the mechanisms that take place within and develop organic matter management options for soils of different textures.

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