NATURAL CARBON-13 DISTRIBUTION IN FORESTED AND CULTIVATED GLEYSOLS

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ABSTRACT

Natural ^{13}C abundance was measured in two Gleysols, one from a forest and one which had been under continuous corn for more than 25 yr. $\delta^{13}C$ values increased slightly with depth in the forest soil. In the corn soil, $\delta^{13}C$ values were similar throughout the plow layer but lowest in the deepest layer sampled, 30-50 cm. Between 29 and 35% of the carbon in the plow layer of the cultivated soil was derived from corn. The 0-5 cm layer of each soil was separated into particle size fractions; $\delta^{13}C$ values indicated that the sand fraction had the largest proportion of carbon derived from corn whereas the coarse silt had the smallest proportion.

INTRODUCTION

The heavy carbon isotope, ^{13}C, accounts for about 1% of all carbon atoms in nature. The proportion of ^{13}C in natural material varies as a result of isotopic fractionation during physical, chemical and biological processes.

Plants with a C_3 photosynthetic pathway reduce CO_2 to 3-C compounds using an enzyme (RuBP carboxlyase) which discriminates against ^{13}C, resulting in low $\delta^{13}C$ values in the plant material. The more efficient C_4 plants reduce CO_2 to 4-C compounds using an enzyme (PEP carboxylase) which discriminates less against ^{13}C; thus the plant material in C_4 plants has relatively higher $\delta^{13}C$ values.

There is little ^{13}C enrichment during the transformation of plant residues into soil organic matter (Stout et al., 1981) so the ^{13}C content of soil organic matter corresponds closely to the ^{13}C content of the plant material from which it is derived. Consequently, the introduction of C_4 plants to soil previously developed under C_3 vegetation results in the soil organic matter containing two isotopically different sources of carbon and provides a means of following changes in soil organic matter turnover with changes in vegetation cover. Several investigators have used this isotopic method to estimate organic matter turnover in tropical (Martin et al., 1990), subtropical and temperate soils (Balesdent et al., 1987; Balesdent et al., 1988).

The objective of this study was to assess the effects of cultivation on organic matter in a Gleysol and use the natural ^{13}C distribution to partition the soil organic matter as to origin.

MATERIALS AND METHODS

The soils used in this study are classified as Orthic Gleysols (Canada Soil Survey Committee, 1978). The cultivated soil was tile drained and had been under continuous corn for more than 25 yr. Tillage operations include fall moldboard plowing with secondary tillage with an offset disk in the spring. Three pits were excavated in both the corn soil and the soil of a mixed hardwood forest within 3 km. Soil samples were taken from the 0-5, 5-10, 10-15, 15-30, and 30-50 cm depth of each pit. Bulk density was estimated using soil cores in the forest soil; a nuclear probe was used at the cultivated site. In the latter technique gamma ray attenuation is used to measure wet bulk density and volumetric water content (Culley and McGovern, 1990) and dry bulk density is calculated from these values.

Soil samples were mixed, air-dried and sieved through a 2 mm sieve which removed plant fragments coarser than 2 mm. Soil samples were separated into particle size fractions by sieving and sedimentation. The organic carbon content of samples were determined using a combustion method with direct titration of the evolved CO_2 as carbonic acid in a NaOH trap (Tiessen et al., 1981). The mass of organic carbon per hectare was calculated as follows:

$$Mg\ C\ ha^{-1} = OC * BD * L * 0.1$$

where OC = organic carbon concentration mg C g^{-1} soil, BD = bulk density (Mg m^{-3}), L = layer thickness (cm).

Samples of leaves, surface roots, twigs and bark were collected from the forest site and corn leaves, roots, cobs with grain and stalks were collected from the cultivated field prior to harvest. Plant and litter samples were oven dried at 60° C and ground in a laboratory mill.

The $\delta^{13}C$ values were determined by combustion of 3 mg C mixed with CuO (1:50) in the vacuum-combustion system described by Schoenau and Bettany (1988). Purified CO_2 was collected in breakseals and run through a VG Isogas SIRA 12 spectrometer.

The natural abundance of heavy isotopes is expressed [as parts per thousand (‰)] relative to the international standard PDB using delta units (δ). The $\delta^{13}C$ value is calculated from the measured carbon isotope ratios of the sample and standard gases as:

$$\delta^{13}C(‰) = [(R\ sample - R\ standard)/R\ standard] \times 10^3$$

where R is the mass 45/44 ratio of the sample or standard gas.

The proportion of carbon derived from corn residues was calculated as:

$$X = (\delta - \delta_f)/(\delta_{cr} - \delta_f) \times 100$$

where δ = $\delta^{13}C$ value of sample from cultivated soil, δ_{cr} = -13.1‰, the $\delta^{13}C$ value of corn residues (excluding cobs and grain), and δ_f = $\delta^{13}C$ value of sample from forest soil.

RESULTS AND DISCUSSION

^{13}C values of plant material and soil

The $\delta^{13}C$ values of forest plant parts ranged from a minimum of -28.3‰ for surface roots to a maximum value of -25.5‰ for bark. Corn plant parts had higher $\delta^{13}C$ than forest plant parts and ranged from -12.8 to -13.4‰ (Table 1). Thus, the range of $\delta^{13}C$ values for plant parts from C_3 (forest) and C_4 (corn) species did not overlap and the average values for all plant parts differed by approximately 14‰, which is consistent with the survey by Smith and Epstein (1971). Variation among corn plant parts was 0.5‰ and was lower than that in the forest plant parts.

The $\delta^{13}C$ values show a consistent increase (2‰ total) with depth in the forest soil profile (Table 2). This phenomenon has been noted in other studies (O'Brien and Stout, 1978; Vitorello et al., 1989; Martin et al., 1990) and may be accounted for by any or all of the following:

i)   Migration and redeposition of clay which has a higher ^{13}C content than that of the whole soil. In the case of Alfisol "lessive" soils, Becker-Heidmann and Scharpenseel (1986) suggested that protected clay-humic complexes (^{13}C enriched) migrated a shorter distance than young soluble carbon and became insoluble in the B horizons.

ii)   Change in isotopic composition of the forest vegetation with time. Atmospheric ^{13}C-CO_2 has decreased by approximately 1.2‰ over the past 130 years (Freidli et al., 1986). The dilution of ^{13}C content of the atmosphere has been attributed to fossil fuel combustion and deforestation.

iii) Certain biochemical fractions of plant litter are slightly heterogeneous isotopically and decompose at different rates. Cellulose and hemicellulose are 1-2‰ more enriched in ^{13}C, whereas lignin is 2-6‰ lower in ^{13}C than whole plant tissue (Benner et al., 1987). Lignin decomposes more slowly than cellulose and the isotopic composition of litter may change during decomposition.

The $\delta^{13}C$ values of the corn soil profile do not show a consistent change with depth. The layers comprising the plow layer have similar $\delta^{13}C$ values, indicating that mixing of corn residues with soil occurred with plowing.

Soil organic carbon in forest and cultivated Gleysols

The concentration of organic carbon in the forest soil showed a sharp decline with depth whereas in the corn soil it was similar in the layers down to 30 cm (Table 3). The concentration of organic carbon in the surface 5 cm was an order of magnitude higher in the forest soil than in the corn soil. These data reflect the large amount of organic matter in the forest which is concentrated on the surface of the soil.

The mass of organic carbon in the surface 10 cm of the forest soil was 3-4 times greater than that of the corn soil (Table 3). Below 10 cm the quantity of organic carbon in the forest and corn soil was similar. The amount of organic carbon to 50 cm depth was 132 Mg ha^{-1} in the forest soil and 74 Mg ha^{-1} corn soil. Thus, cultivation resulted in a loss of 44% of the organic carbon content of the soil. Detailed records of the start of cultivation were not found, but the period of cultivation was estimated at 80-100 yr, based on the history of settlement in the area.

The mass of organic carbon in the corn soil increased slightly in each depth increment to 30 cm. A thin band of residues between 20-25 cm which was observed during excavation of the corn soil may account for this increase in carbon with depth. These buried residues are the result of the inversion of crop residues during moldboard plowing.

Carbon derived from corn

The proportion of carbon derived from corn was greatest in the top 5 cm, was similar for depth increments to 15 cm and ranged from 29-35% (Table 3). The lowest proportion of carbon derived from corn was found deepest in the profile, at 30-50 cm. This depth is below the plow layer and the corn carbon is probably from corn roots and soluble corn organic material. The slightly lower proportion of carbon derived from corn in the 15-30 cm layer was probably due to the incorporation of soil low in corn carbon from below the plow layer.

More than 16 Mg C ha^{-1} was derived from corn and contained in the top 50 cm of the soil profile. More than 60% of this carbon was contained within the top 15 cm.

The δ^{13}C values of the particle size fractions from the top 5 cm of the forest soil were similar to the average δ^{13}C values of the forest whole soil and litter. In the forest soil, the variation between particle size fractions was 1.1‰. In contrast, the δ^{13}C values of particle size fractions in the corn soil varied by 4‰. The δ^{13}C value of the corn soil sand fraction was about 2‰ higher than that of the whole soil indicating it was relatively enriched in ^{13}C and in carbon derived from corn. This enrichment would be expected for the fraction in which non-decomposed residues predominate and indicates that the turnover of organic matter is the most rapid in the sand fraction. The readily decomposable

nature of organic material in the sand fraction has been observed in mineralization studies (Christensen, 1987; Gregorich et al., 1989).

The fractions smaller than sand size had lower $\delta^{13}C$ values than did whole soil, indicating less enrichment of carbon derived from corn and slower turnover of carbon. The proportion of carbon derived from corn decreased sharply to 16% in the coarse silt fraction and increased to about 26% in the fine silt and fine clay. The slow turnover of carbon in the coarse silt indicates the organic matter is older and more stable. Anderson and Paul (1984) used radiocarbon dating to show that the organic carbon associated with the coarse clay/fine silt was the oldest fraction. Tiessen and Stewart (1983) found that the stability of organic matter increased from sand to fine silt and decreased from fine silt to fine clay. The differences in observations of the stability and age of organic matter associated with particle size fractions by our study and these studies may be due to genetic differences in the soils, as well as differences in mineralogy, management and crop history.

CONCLUSIONS

Cultivation of C_4 plants on a soil previously under C_3 vegetation allowed the partitioning of soil organic matter as to origin. Measurement of natural ^{13}C abundance was used to estimate the quantity of carbon derived from corn on the whole soil and particle size fractions of a Gleysolic soil in Ontario. About one-third of the organic matter in the top 15 cm had turned over since the start of continuous cropping to corn more than 25 yr ago. The turnover of organic matter was most rapid in the sand fraction and slowest in the coarse silt fraction.

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Table 1. Variations in the δ^{13}C values (‰) of litter material from a forest and corn Gleysol (Mean ± Std. Dev.).

Plant parts

	Forest litter
Leaves	-27.6 ± 0.4
Surface roots	-28.3 ± 1.6
Twigs	-27.8 ± 0.5
Bark	-25.5 ± 0.4
Average of all plant parts	-27.3 ± 1.35
	Corn litter
Leaves	-13.4 ± 0.6
Surface roots	-12.8 ± 0.5
Cobs & grain	-13.0 ± 0.6
Stalks	-13.1 ± 0.1
Average of all plant parts	-13.1 ± 0.5

Table 2. Variations in the δ^{13}C values (‰) with depth in Gleysols under a forest and corn crop (Mean ± Std. Dev.).

Depth (cm)	**Forest soil**	**Corn soil**
0-5	-28.3 ± 0.3	-22.9 ± 0.5
5-10	-27.3 ± 0.2	-23.2 ± 0.5
10-15	-26.7 ± 0.5	-22.5 ± 0.6
15-30	-26.7 ± 0.1	-23.9 ± 0.2
30-50	-26.2 ± 0.3	-25.3 ± 0.7

Table 3. Concentration and mass of organic carbon in forested and cultivated Gleysols and the proportion and quantity of carbon derived from corn.

Depth	Organic carbon		Carbon derived from corn	
cm	mg g^{-1}	Mg ha^{-1}	%	Mg ha^{-1}
Forest soil				
0-5	140.7	45.7		
5-10	87.2	28.3		
10-15	51.3	16.7		
15-30	12.8	27.8		
30-50	4.3	13.2		
Corn soil				
0-5	17.6	10.2	35	3.6
5-10	14.7	10.4	29	3.0
10-15	17.2	11.4	30	3.4
15-30	12.9	26.5	20	5.3
30-50	4.9	15.2	7	1.1

Table 4. $\delta^{13}C$ values (‰) of particle size fractions in forested and cultivated Gleysols and the proportion of carbon derived from corn.

Soil fraction	Forest soil	Corn soil	Carbon From Corn (%)
Whole soil	-28.3	-22.9	45
Size fraction:			
Sand	-27.0	-20.8	45
Coarse silt	-27.0	-24.8	16
Fine silt	-27.8	-24.0	26
Coarse clay	-27.0	-23.6	24
Fine clay	-26.7	-23.1	27