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Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France

DOMINIQUE ARROUAYS and PHILIPPE PELISSIER
Institut National de la Recherche Agronomique, S.E.S.C.P.F., B.P. 81, 33140, Pont de la Maye, France and Ecole Nationale d'Ingénieurs des Travaux Agricoles, 1 cours du Général de Gaulle, 33175, Gradignan, France

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Abstract

Soil samples from forest and agricultural sites in three areas of southwest France were collected to determine the effect of forest conversion to continuous intensive corn cropping with no organic matter management on soil organic carbon (C) content. Soils were humic loamy soils and site characteristics that may affect soil C were as uniform as possible (slope, elevation, texture, soil type, vegetation).

Three areas were selected, with adjacent sites of various ages of cultivation (3 to 35 yr), and paired control forest sites. The ploughed horizon (0-Dt cm) and the Dt-50 cm layer were collected at each agricultural site. In forest sites, each 10 cm layer was collected systematically down to 1 meter depth. Carbon concentrations were converted to total content to a given depth as the product of concentration, depth of sample and bulk density, and expressed in units of kg m^{-2}. For each site and each sampled layer, the mineral mass of soil was calculated, in order to base comparisons on the same soil mass rather than the same depth.

The pattern of C accumulation in forest soils showed an exponential decrease with depth. Results suggested that soil organic carbon declined rapidly during the first years of cultivation, and at a slower rate thereafter. This pattern of decrease can be fitted by a bi-exponential model assuming that initial soil organic carbon can be separated into two parts, a very labile pool reduced during the first rapid decline and more refractory fractions oxidizing at a slower rate. Sampling to shallow depths (0-Dt cm) resulted in over-estimation of the rate of carbon release in proportion to the initial amount of C, and in under-estimation of the total loss of C with age. The results for the 0–50 cm horizon indicated that losses of total carbon average about 50% in these soils, ranging in initial carbon content from 19 to 32.5 kg m^{-2}. Carbon release to the atmosphere averaged 0.8 kg m^{-2} yr^{-1} to 50 cm depth during the first 10 years of cultivation. The results demonstrate that temperate soils may also be an important source of atmospheric carbon, when they are initially high in carbon content and then cultivated intensively with no organic matter management.

Introduction

Changes in carbon storage in soils have recently received attention because of their possible influence on the global atmospheric carbon budget (Bouwman, 1989; Detwiler, 1986; Houghton et al., 1991; Lugo and Brown, 1993; Mann, 1986; Schlesinger, 1986, 1991). Several recent studies have suggested that conversion of forest lands to permanent cropping decreases the soil organic carbon pool, rapidly in the first years, and at a slower rate thereafter, approaching a new equilibrium after 30 to 50 yr (Brown and Lugo, 1990; Houghton et al., 1983; Mann, 1986; Schlesinger, 1986).

Available studies on tropical soils demonstrate a rapid decline in organic matter due to continuous cultivation (e.g. Allen, 1985; Brams, 1971; Brown and Lugo, 1990; Lugo and Brown, 1993). In temperate zones, deforestation is no longer common because of agricultural overproduction. The general trend (especially in the European Community) tends towards afforestation of cropped lands rather than deforestation. However, many forests have been converted to agricultural lands since the early fifties. In temperate zones, studies concerning changes due to clearing of forests and agricultural conversion of native vegetation have shown losses from 70% to gains of up to 200% in soil organic carbon, depending on soil type, depth of sampling, erosion, cropping system used and soil treatments applied (e.g. Liang and MacKenzie, 1992; McGill et al., 1981; Mann, 1986; Sommerfeldt et al., 1988).

Corn is an important crop in southwest France. In this area, several long-term studies have evaluated changes in soil organic C under continuous corn for periods of 10 to 30 year, in different soil types and for various soil management practices (Delas et al., 1967, Juste et al., 1973; Juste, 1989). However, these studies have failed to report carbon storage of forest soils and/or have been restricted to shallow depths. These studies also lacked bulk density information, thus changes in the organic carbon pool cannot be evaluated.

In southwest France, thick humic acid soils have developed from Quaternary silty alluvial deposits [Veracrisols (Arrouays et al., 1992)]. On these soils, most forest lands have been converted to continuous intensive corn cropping. The loss of soil C upon conversion to intensive agriculture has been shown to be proportional to the initial amount of C (Allen, 1985; Mann, 1986; Brown and Lugo, 1990; Weaver et al., 1987), thus the losses of C in Veracrisols may be significant.

The objectives of this study were: (i) to evaluate changes in carbon storage in these soils, after durations of cultivation ranging from 3 to 34 years, (ii) to test available simple models for estimating carbon content evolution, (iii) to discuss the combined effects of sampling and tillage depths on carbon content evaluation.

Materials and methods

Study sites

Soil samples were collected from an oceanic zone of the French Pyrenean piedmont (southwest France), from three mature forests and from various ages of cleared forests converted to corn-cropped sites (Table 1). Agricultural sites were located adjacent to forest sites. It was not possible to find the same number of sites for each age adjacent to each forest control site. Selected sites were quite flat and soil type and texture were as uniform as possible (Table 1). Soils were acid humic silty loams classified as "Veracrisol" in the French pedological reference base (Arrouays, 1992). In soil taxonomy they can be classified as Vermic Haplumbrepts (Arrouays et al., 1992). The three areas (noted L, H, M, in this report) of sampling were located as follows: L = 43°32′N 0°40′W, H = 43°39′N 0°41′W, M = 43°34′N 0°18′W. The areas receive about 1150 (L), 1100 (H) and 1000 (M) mm yr^{-1} of rainfall, and the mean annual temperature is about 13 °C (Choisnel et al. 1987). Sites were at an elevation of 105 (L), 110 (H) and 200 (M) meters, with slopes of <2%.

Forest sites were of mature Maritime Pine (*Pinus Pinaster* Ait.). Understory vegetation was mainly composed of *Ulex nanus*, *Molinia coerulea*, *Pteris aquilina*, and *Ulex europaeus*.

Landowners provided information on the age and history of sites. All agricultural sites had been converted to intensive continuous crop cropping. Neither manure, nor any organic material had been applied. Stalks were returned to the soil.

Soil sampling

Samples of forest soils were systematically collected from soil pits in July 1992. Each 10 cm layer was sampled down to 1 m depth, except for site H, where an additional 0–5 cm depth of the organic horizon was observed and collected. Samples were collected on the four walls of a soil

Table 1. Site characteristics: Texture analysis, age of cultivated land, bulk density of tilled horizons

Site	Age of cultivated land (yr)	Clay	Silt	Sand	Bulk density Tilled horizon
		(%)			
Zone L					
LF	0	27.5	60.4	12.1	
LC1	17	21.9	67.4	10.7	1.27
LC2	19	22.4	64.4	13.2	1.49
LC3	30	24.1	65.6	10.3	1.44
LC4	17	24.9	66.2	8.9	1.24
LC5	8	21.8	68.8	9.4	1.41
LC6	5	21.6	69.9	8.5	1.47
Zone M					
MF	0	19.1	71.3	9.6	
MC1	24	19	72	9	1.28
MC2	27	20.3	71.1	8.6	1.24
MC3	3	23.5	67	9.5	1.35
Zone H					
HF	0	18.6	70	11.4	
HC2	22	21.2	66.6	12.2	1.21
HC3	32	15.6	71	13.4	1.32
HC4	19	20.1	61.2	18.7	1.28
HC5	31	15.4	73.2	11.4	1.52
HC6	12	16.5	66.5	17	1.31

pit. Then, the pit was enlarged, and four new samples were collected. The eight samples of each layer were mixed to obtain 1 sample for texture and carbon determinations. Five samples of known volume were taken for each layer, using metal rings, for bulk density determination.

Samples of agricultural soils were systematically collected from eight 60 cm depth soil pits for each site. Depth of soil tillage (Dt) was measured on each pit. 0-Dt and Dt-50 cm layers were collected. For each site and for both of the two layers, samples were mixed as described above. One sample of known volume was taken for each layer of each pit for bulk density determination.

Laboratory analysis

Samples for C and texture analysis were oven dried to constant weight at 105 °C, and sifted through a 2 mm mesh. None of the soils contained particles >2 mm. Particle-size analysis and organic carbon were analyzed by standard techniques of the French Normalization Association (AFNOR, 1987).

Samples for bulk density determinations were oven-dried to constant weight at 105 °C and weighed.

For each sample of sites L and M, densimetric fractionation of soil organic matter was performed by means of centrifuging $CHBr_3/CH_3CH_2OH$ liquid organic mixtures (density = 2; 10 g soil/50 mL), using the method given by Monnier et al., (1962). Light fractions were weighted. Carbon content of light fractions was determined by dry combustion.

Data analysis

Bulk densities of each layer of each site were averaged to obtain a mean value for each sample. Carbon concentrations were converted to total content to a given depth as the product of concentration, depth of sample and bulk density, and expressed in units of $kg\,m^{-2}$. For each site and each sampled layer, the mineral mass of soil was calculated, in order to base comparisons on the same soil mass rather than the same depth (Ayabana et al. 1976; Brown and Lugo, 1990; Lugo and Brown, 1993; Nye and Greenland, 1964). For each layer of each agricultural site, the theoretical depth of the paired layer of the control forest soil was calculated on the basis of the same total soil mineral mass, and the theoretical initial carbon content was deduced.

Statistical analysis

For each layer of each site the standard error of carbon concentration was calculated and expressed in units of kg m^{-2}. Ninety-five percent confidence intervals of carbon concentrations were reported on figures showing means and fitted curves of carbon concentration evolution with time.

Results

Vertical distribution of carbon in forest soils

The C content in soil under forests declined progressively with depth in the entire profile (Fig. 1). The pattern of accumulation showed an exponential decrease with depth. The C content curve can be fitted by an exponential equation:

$$(C_x - C_1)/(C_2 - C_1) = (e^{-bx} - e^{-bx_1})/(e^{-bx_2} - e^{-bx_1})$$

x and C_x are the mid-point depth and the carbon content of a given sample, x_1 and C_1 the mid-point depth and the C content of the deeper layer, x_2 and C_2 the mid-point depth and the C content of the upper layer. The coefficient b represents the curve of the pattern.

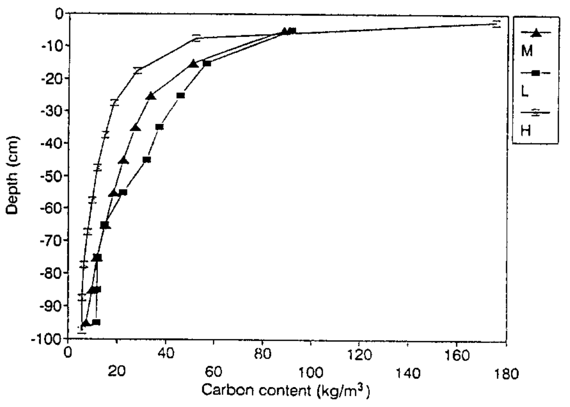

Fig. 1. Vertical distribution of organic carbon in forest sites.

Such typical patterns have already been reported (Arrouays et al., 1992), and appear to characterize C accumulation in Veracrisols.

Soil texture

Results of texture analysis confirmed the textural similarity among all sites and areas (Table 1). Clay content ranged from 15.4 to 27.5%, while silt content ranged from 60.4 to 73.2%. However, the soils of the H zone had less clay than the other sites.

Carbon content

Figure 2 shows the variation in C content of the tilled horizon (0-Dt cm), with age of corn-cropped site. Zero age points are mean values of carbon content of each forest site, based on a mass of mineral soil equal to that of agricultural tilled layers. Horizontal bars are 95% confidence interval values calculated for each site. Carbon content decreased with age, at a rapid rate during the first years, and at a slower rate thereafter. For ages >10 yr, the tilled horizons of corn-cropped sites contained from 30 to 51% of the initial C content of forest sites.

Variation in C content of the under-tillage

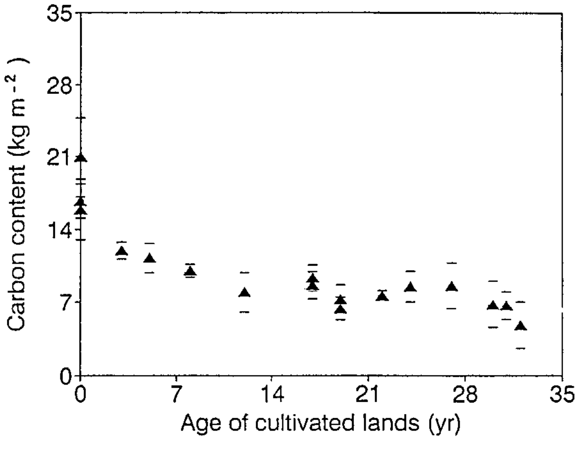

Fig. 2. Variation in C content with age of corn-cropped sites (0-Dt cm). Zero age values are mean C content of the forest sites (horizontal bars are 95% confidence interval values).

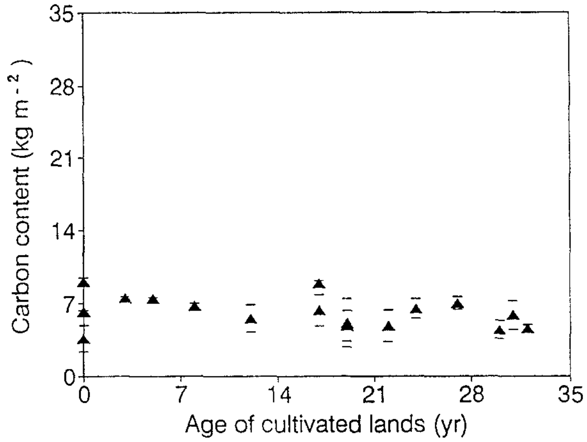

Fig. 3. Variation in C content with age of corn-cropped sites (Dt-50 cm). Zero age values are mean C content of the forest sites (horizontal bars are 95% confidence interval values).

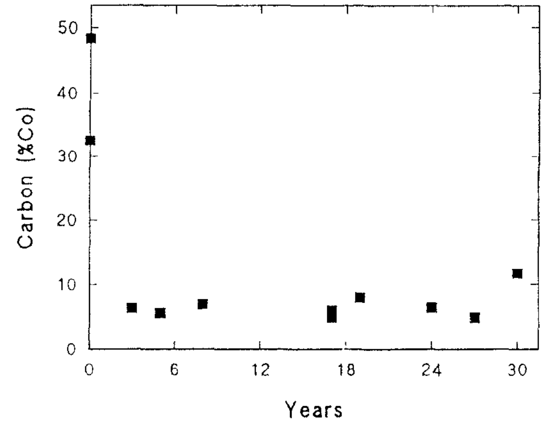

Fig. 5. Variation in C content of light fractions (expressed as the percentage of the initial total carbon amount) for 0-Dt layers of sites L and M.

horizon (Dt-50 cm) tended to decrease slightly (Fig. 3). Although there was a general pattern of slightly decreasing soil C with increasing age of agricultural lands, several cropped sites (e.g., all H agricultural sites) had a C content higher than their paired forest site, which may appear surprising. None of the Dt-50 cm layers showed a significant decrease during the first years of cultivation.

Variation of total C content of the 0–50 cm layers showed an important decrease during the first years, and decreased at a lower rate thereafter (Fig. 4). The 0–50 cm layer exhibited a decreasing rate slower than that of the tilled horizon.

Carbon content of light fractions

Figures 5 and 6 show the evolution of carbon content of light fractions for 0-Dt and 0–50 cm layers of sites L and M. Carbon content of light fractions is expressed as the percentage of initial total C content in forest sites.

For 0-Dt layers, light fraction carbon amounts in forest sites from 33 to 48% of the initial

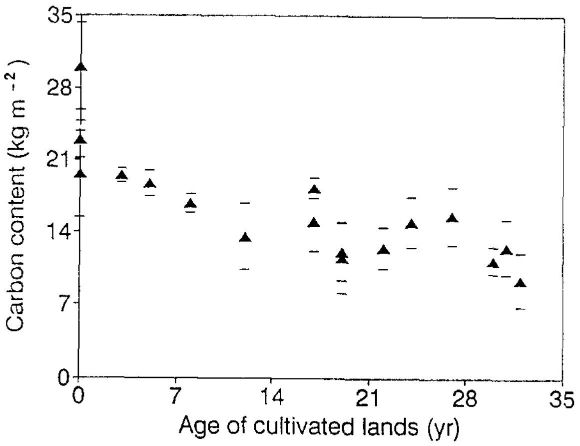

Fig. 4. Variation in C content with age of corn-cropped sites (0–50 cm). Zero age values are mean C content of the forest sites (horizontal bars are 95% confidence interval values).

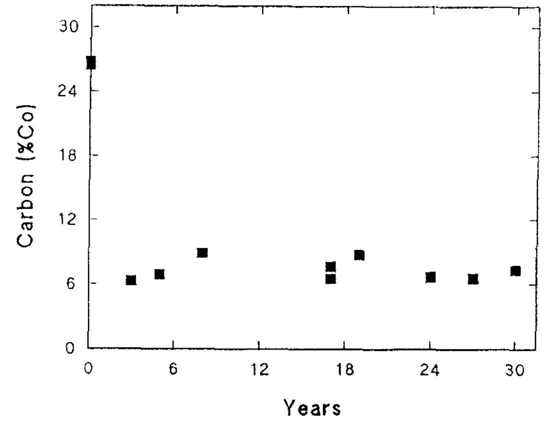

Fig. 6. Variation in C content of light fractions (expressed as the percentage of the initial total carbon amount) for 0–50 layers of sites L and M.

carbon pool. They exhibited a sharp fall during the first years of cultivation and seemed to remain quite constant thereafter.

For 0–50 cm layers the initial organic carbon pool in forest sites can be divided into a light fraction (26%), and a more evolved fraction (74%). Light fraction carbon amounts exhibited a sharp fall after the first years of cultivation, and they seemed to reach a plateau thereafter. It is striking to observe that the value of this plateau is of the same order as the annual C input of corn stalks.

Discussion

Modelling the rate of soil carbon release

Results suggest that soil organic carbon declines rapidly during the first years of cultivation, and at a slower rate thereafter. This pattern of decrease can be fitted by a bi-exponential model assuming that initial soil organic carbon can be separated in a very labile pool reduced during the first rapid decline, and more refractory fractions oxidizing at a slower rate.

For the 0–50 cm layer, the model retained follows the equation (Fig. 7):

$$C = 17.9\,e^{-0.013t} + 6.3\,e^{-0.307t}\,.$$

According to this model, the initial soil carbon content can be divided into a 26% fraction of very labile organic matter, and a 74% more recalcitrant fraction. After clearing, there is a 5 yr period in which organic carbon declines by 25%, followed by a second period in which a slower rate of decline is observed. This model is coherent with results of light fraction C decrease: it has been shown that the materials removed in the light fractions were mainly undecomposed or partly humified plant residues of plants and other soil organisms while heavier fractions were more stabilized components [e.g. Ford et al. (1969); Oades and Ladd (1977); Turchenek and Oades (1979)]; in this study, the more decomposable organic pool was found to decrease rapidly, while more recalcitrant fractions showed a slower decrease. Jenkinson and Rayner (1977) also suggested that the organic pool can be divided into compartments whose turnover time are different: (i) soil biomass decomposable and resistant plant material, with half-lives shorter than 3 yrs (ii) physically and chemically stabilized organic matter with much longer turnover time. This model is also coherent with the assumptions used by Houghton et al. (1991), [20% in 5 yr]. On a recently cleared Veracrisol, Delas et al. (1967) showed a similar decrease of soil organic carbon during the first years of cultivation (15% in a 3 yr period). During a 10 yr period of continuous corn-cropping of a Veracrisol (cleared a few years before the beginning of the experimentation), Juste et al. (1973) demonstrated an exponential decrease of organic carbon with a coefficient (−0.015) very close to the figure developed by the present study (−0.013). These data are not sufficient to predict whether a steady state will be reached after this second decline. Therefore, it is dangerous to extrapolate trends for a long-term global prediction.

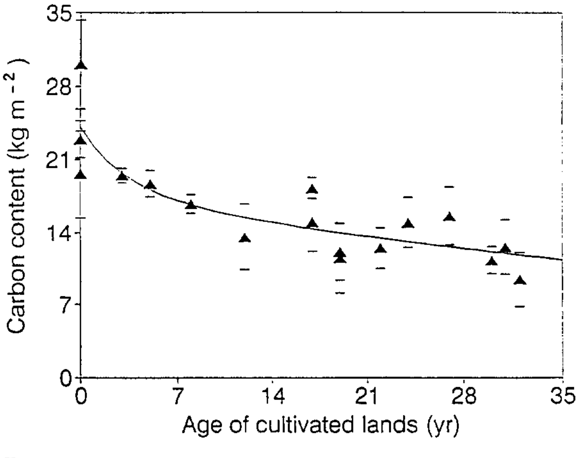

Fig. 7. Variation in C content with age of corn-cropped sites (0–50 cm). Fitted bi-exponential model.

Modelling the decrease of the 0-Dt cm layer organic carbon leads to a somewhat different equation (Fig. 8).

$$C = 10.8\,e^{-0.016t} + 7.06\,e^{-0.423t}\,.$$

According to this model, the proportion of labile organic matter seems to be larger (about 40%) than in the 0–50 cm layer. Rates of carbon release are also superior, and the curve of the second decline (−0.016) is similar to the results

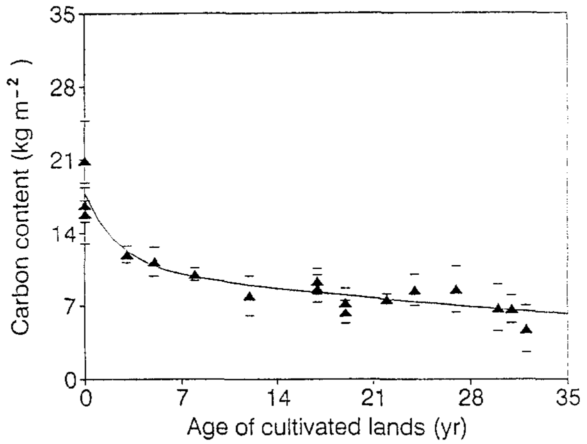

Fig. 8. Variation in C content with age of corn-cropped sites (0-Dt cm). Fitted bi-exponential model.

obtained by Juste et al. (1973). As shown in Figure 5, the proportion of light fraction C content in the topsoil is greater than in the 0–50 cm layer. Therefore, the results of light fraction C determination and the compartmentalized model of C losses are coherent.

Effects of sampling and tillage depths

Sampling to shallow depths results in over-estimating the rate of carbon release in proportion of the initial amount of C, and in under-estimating the total loss of C with age. Sampling to 25 cm fails to include a large proportion of C content, as reported by Brown and Lugo (1990), and Sanchez (1976). It may also over-estimate the curve of the C loss patterns, as greater changes are expected to occur in the ploughed layer.

In this study, it was also surprising to observe, in several sites, an increase in C content after clearing in the Dt-50 layer. An explanation might be the enlarged input of C via roots due to enhanced C-translocation by corn as compared to trees, but this may also be due to the inability to satisfactorily document the tillage history of the cultivated sites. For data analysis, comparisons were based on the same mineral soil mass, in order to calculate the initial C content of the forest sites corresponding horizons. This analysis is relevant for the 0–50 cm horizon, because conversion of forest land to agriculture often resulted in increases in bulk density, and because the tillage depth was never deeper than 50 cm. However, for the 0-Dt horizon, Dt may have changed with age, especially for the first tillage after clearing. This tillage may have been deeper than that used for calculations.

The initial carbon content of the ploughed horizon is highly related to the depth of first ploughing (Fig. 9), because of the initial carbon content patterns. The data analysis may have thus over-estimated the C initial content of the 0-Dt horizon, and under estimated the initial C content of the Dt-50 cm layer. This may explain why a C content increase was observed for several sites. The effects of land clearing and tillage methods must be taken into account in choosing sampling depth, and for modelling the rate of soil carbon release.

Changes in carbon storage after cultivation

The results for the 0–50 cm horizon indicate that, after 35 yr of continuous corn-cropping, losses of total carbon average about 50% in these soils, ranging in initial carbon content from 19 to 32.5 kg m^{-2}. A shown in Figure 7 and the fitted equation, these data are not sufficient to predict whether a steady state will be reached after this decline. Therefore, it is dangerous to extrapolate trends for a long-term global prediction. The results suggest that the first period of sharp fall in C content is related to the rapid decomposition of the labile C light fraction.

These losses are greater than the losses evaluated for different soil-types by Mann (1986). In

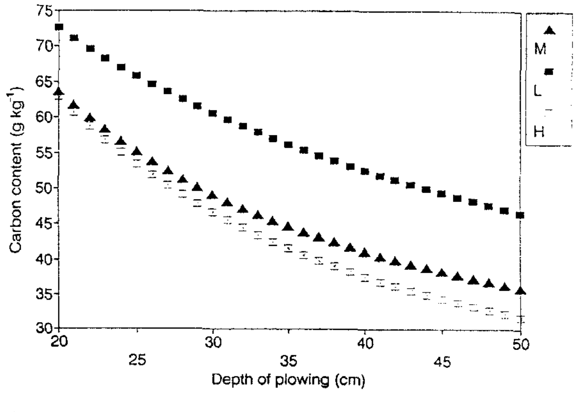

Fig. 9. Variation in initial C content of the top-soil horizon with depth of first ploughing.

this study, forest soils accumulated large amounts of carbon. Jenny (1980) and Mann (1986) suggested that changes in microclimate due to cultivation may result in more rapid mineralization in soils initially high in carbon content. Intensive agricultural use with no regard to organic matter management reduces soil organic carbon with length of time under cultivation. Losses of about 50% are observed after 10 to 30 years of corn cropping with no organic matter management. Many studies (see e.g. Van Veen and Paul, 1981; Voroney et al. 1981) have shown this disturbance of the soil due to cultivation of native ecosystems. Organic matter return in the form of stubble may play a minor role since input of C via roots of living plants represents a significant source of C-input all through the growing season. Both added straw and manure have been reported to increase soil organic C (Liang and MacKenzie, 1992; Sommerfeldt et al. 1988). In the present study, carbon release to the atmosphere due to continuous corn-cropping averaged 0.8 kg m^{-2} yr^{-1} to 50 cm depth during the first 10 years of cultivation. Similar rates of carbon release have also been shown in tropical soils (Brown and Lugo, 1990).

Conclusion

Results of light fraction C determination were consistent with a bi-compartimentalized model: Both total C content evolution fitting and densimetric fractionation lead to similar percentages of very labile and more recalcitrant pools. Therefore, a bi-exponential model can be used to describe C decrease in these soils. Sampling to shallow depths resulted in over-estimating the rate of carbon release in proportion to the initial amount of C, and in under-estimating the total loss of C with age. Therefore, studies restricted to shallow depths appear not to be relevant for studying the role of soils as sources of atmospheric carbon, and sampling must concern a depth greater than the present observed tillage depth.

The rate of carbon release during the first yr of cultivation was similar to values observed in tropical soils (Brown and Lugo, 1990). These results demonstrate that temperate soils may also be an important source of atmospheric carbon, when they are initially high in carbon content and then cultivated intensively with no organic matter management.

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