The Role of Terrestrial Vegetation in the Global Carbon Cycle:
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CHAPTER 3
Organic Carbon in Soils of the World

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ABSTRACT

The loss of organic matter from soil is mainly the result of the clearing of forests for grassland or cropland. On the basis of the assumptions outlined here, the annual loss of organic carbon from the world's soils is between 2.5×10^{15} g and 7.4×10^{15} g, with 4.6×10^{15} g being considered a realistic estimate. These amounts are 0.2, 0.5 and 0.3 per cent of the total organic carbon (1477×10^{15} g) currently estimated to exist in the world's soils. Since the total organic carbon in soil in prehistoric times has been estimated as 2014×10^{15} g, the loss since then has been 537×10^{15} g, or 27 per cent of the amount present prior to the spread of civilization in the last two millennia.

3.1 INTRODUCTION

The loss of organic matter from forest soils following disturbance is an important source of CO_2 for the atmosphere. Bolin (1977) and Schlesinger (1977, 1983) have estimated the net loss of organic carbon from the world's soil. Bolin states that if it is assumed that from 25 to 50 per cent of the presently cultivated land has been converted from forest land since the early nineteenth century, the release of organic carbon from the soil to the atmosphere during the last two centuries can be estimated at 10 to 40×10^{15} g, with an annual loss at 0.1 to 0.5×10^{15} g. Kovda (1974) has estimated the total humus in the earth's soil at 2400×10^{15} g, equivalent to approximately 1400×10^{15} g of carbon. Bohn (1976) stated that earlier in this century the organic carbon in the world's soil was estimated at 710×10^{15} g. This estimate was based on the carbon content of nine North American soils as shown in a 1915 soil textbook. Using the FAO/UNESCO soil map (1978) for South and North America, and the soil map of Ganzen and Hadrich (1965) for the other continents, Bohn estimated that there are $3000 \pm 500 \times 10^{15}$ g of organic carbon in the world's soil. Although he did not try to estimate the amount of CO_2 released to the atmosphere, Bohn (1976, p. 469) says that 'The decay of soil organic matter is one of the largest CO_2 inputs to the atmosphere'.

A few authors have tried to calculate the oxidation losses of organic matter in soils. Greenland and Nye (1959) and Nye and Greenland (1960) studied the effect of shifting cultivation on some West African soils. An excellent review has been given by Young (1976). More recently models for the decomposition of organic matter in the soil have been developed (Rayner, 1978). Unfortunately the approach used by these authors cannot be adopted for a world-wide study of soils because information is available only for a limited number of soils.

Schlesinger (1977, 1983) has calculated the mean carbon content in 11 ecosystem types and multiplied the mean by the amount of land included in these ecosystems. He offered a preliminary estimate that the earth's total soil carbon is 1515×10^{15} g. The annual release of soil carbon by his estimate is about 0.8×10^{15} g. This figure is based on the assumption that the annual conversion of forest to cultivated land is 15×10^{6} ha and that the average carbon content of 131 t/ha in forest soil drops to 78.6 t/ha after conversion to cultivation, a decline of 40 per cent.

3.2 PROCEDURE

Any attempt at this time to compute the net annual release of CO_2 from the soil humus of all the soils of the world can only be a rough approximation. Detailed soil studies have only been made of a small part of the earth's land area, and 80 per cent of all soils have not been studied at all (Dudal, 1978). Most analyses of soils are incomplete because they have been carried out for agricultural rather than more general purposes.

Although organic matter is often present in the soil to a depth of 1 or 1.5 m, most is in a surface layer of from 1 to 20 cm. Carbon also exists in the mineral part of soils or in the soil solution, mainly as carbonates and bicarbonates of calcium, magnesium and sodium. Carbonates are ignored in this paper because the amount of CO_2 released to the atmosphere from mineral sources is small. The organic matter (litter) lying on top of the soil surface is also ignored because it is considered to be part of the biomass. The organic matter in soil consists of:

(a) living plant roots,
(b) dead but little-altered plant remains,
(c) partly decomposed plant remains,
(d) colloidal organic matter, being the humus proper—often some 60 to 70 per cent of the total organic matter in soils (Schnitzer and Khan, 1978),
(e) living microorganisms (bacteria, fungi, protozoans, etc.) and macroorganisms (worms, ants, termites, etc.),
(f) inactive or inert organic matter (coal, burned vegetation or ash fertilizer).

There are various methods of soil analysis to determine organic matter content (Jackson, 1958). In most analyses the soil material is passed through a two mm sieve after macroscopic plant remains (mainly roots) have been removed. Organic matter content usually is one to five per cent of the dry weight in the surface soil and decreases with depth. The carbon content is generally about 58 per cent of organic matter content (0.58 is the van Bemmelen factor), although in the tropics it is often 45 to 55 per cent. (The van Bemmelen factor is used in this paper.)

The following example gives an idea of the quantity of organic matter in one hectare. A soil with a bulk density of 1.5, and a carbon content of 3 per cent in the 0 to 25 cm layer, 1 per cent in the 25 to 50 cm layer, 0.3 per cent in the 50 to 75 cm layer and 0.1 per cent in the 75 to 100 cm layer, contains 165 t C/ha; the 0 to 25 cm layer contains 113 t/ha, or 68 per cent of the total. In a true chernozem (black earth, or mollisol) the total soil carbon is more than 200 t/ha and the surface layer of 0–25 cm contains only 25 per cent of the carbon because the humus layer is very deep.

The organic matter content in soil depends on soil conditions, present and recent vegetation cover, topography, hydrological conditions, elevation and farm management practices. Soil conditions in turn are most influenced by the soil moisture and temperature regimes, although the biological and mineralogical regimes are also important. For example, soil derived from rocks that are basic (as opposed to felsic) generally contains more organic matter than soil from felsic rocks. Clay content and type also affect organic matter content. Furthermore, the oxidation of organic matter is more rapid in calcareous soil than in non-calcareous soil. Various attempts have been made to correlate the organic matter content of soils in a specific region or country with some of these factors. Young (1976) has provided a summary of processes that affect organic matter content.

Under natural conditions the content of organic matter in soil is constant; the rate of decomposition is equal to the rate of supply of organic matter from plants. The equilibrium is disturbed when forests are cleared and the land is used for agriculture. There is also a decline in organic matter when grassland in the tropics and subtropics is transformed into cropland, or when savannahs are burned. The decline is rapid in the first few years after deforestation and gradually slows over the next 10 to 50 years. Organic matter is also lost through misuse or deterioration of land (soil erosion, salinization, alkalization and soil degradation), and because of the increasing non-agricultural use of land (urbanization and highway construction).

On the other hand, there may be an increase in organic matter when good farm management is practised and organic manure and compost are used, when arid land is irrigated, or where agricultural land is reforested. Histosols (peat soils) contain a considerable amount of carbon.

In the following pages the average soilcarbon content in various soils have been examined in relationship to types of land use. With these data the net loss of soilcarbon and the release of CO_2 to the atmosphere have been estimated as a result of changes in land use, even though precise data on the annual changes in land use are not available. Since land use in prehistoric times is also known within broad limits, it is also possible to calculate the approximate loss of soil carbon since that time as well.

A large amount of data on soil conditions and land use has been studied to establish 37 standard soils with a standard soilcarbon content. The procedure is described in the following sections.

3.3 MAJOR SOILS AND THEIR POTENTIALITIES

Initially, an attempt was made to use the 106 soil units of the FAO/UNESCO soil map as a basis for this investigation. Only a small amount of analytical data on humus content is available, however, and it was often difficult to correlate the soils described in various soil reports with the units of the soil map. Moreover, the soil units of the soil map do not indicate soil moisture and soil temperature regimes. A statistical approach based on the 10 soil orders of the new US soil classification system (Soil Survey Staff, 1975) has been adopted. Buol *et al.* (1973), and Buringh (1979) give short descriptions of the soils belonging to each soil order. The approximate extent of each soil order, and the areas that are potentially arable, non-arable but grazeable, and neither arable nor grazeable, are known (see Table 3.1). (One group, 'Mountain soils', is not subdivided into soil orders on the table.)

Table 3.1 World land area in different soil orders, in millions of hectares (10^6 ha)

Order	Potentially arable	Non-arable but grazeable	Non-arable and non-grazeable	Total	Per cent
Alfisols	640	690	400	1 730	13.1
Aridisols	80	250	2 150	2 480	18.8
Entisols	150	290	650	1 090	8.2
Histosols	1	20	100	120	0.9
Inceptisols	230	230	710	1 170	8.9
Mollisols	630	340	160	1 130	8.6
Oxosols	650	350	120	1 120	8.5
Spodosols	100	210	150	560	4.3
Ultisols	270	330	130	730	5.6
Vertisols	140	60	30	230	1.8
Mountain soils	230	910	1 670	2 810	21.3
Total	3 120	3 680	6 370	13 170	100.0
Per cent	23.7	27.9	48.4	100.0	

SOURCE: Soil Geography Unit, Soil Conservation Service, US Dept. of Agr., Washington, 1973.

Table 3.2 Major land-use types by soil orders in millions of hectares (10^6 ha)

Order	Crop land	Grass land	Forest land	Other land	Total
Alfisols	290	300	800	340	1 730
Aridisols	40	260	0	2 180	2 480
Entisols	80	200	550	260	1 090
Histosols	0	0	100	20	120
Inceptisols	150	200	650	170	1 170
Mollisols	290	680	0	160	1 130
Oxisols	300	300	450	70	1 120
Spodosols	50	150	250	110	560
Ultisols	130	150	400	50	730
Vertisols	60	100	50	20	230
Mountain soils	110	700	800	1 200	2 810
Total	1 500	3 040	4 050	4 580	13 170
Per cent	11.4	23.1	30.1	34.8	100

The potentially arable land is almost 24 per cent of the earth's total land area not covered by ice ($13\,170 \times 10^6$ ha). Similar figures have been published by the President's Science Advisory Committee (1967), Simonson (1967), Kovda (1974) and Buringh *et al.* (1975). Aubert and Tavernier (1972) and Sanchez (1976) have presented figures for soil orders in the tropics. The non-arable and non-grazeable land in Table 3.1 is mainly desert, tundra and high mountains. This classification also includes lithosols and very shallow soils.

3.3.1 Major Soils and their General Land-use Types

Four general land-use types are used in this paper. Table 3.2 shows the estimated amount of acreage of each type, divided into soil orders, in round figures. The totals are in accordance with the (1975) FAO statistical data. The total amount of potentially arable land is 3120×10^6 ha while presently arable land is 1500×10^6 ha, or 11 per cent of the total area (see Table 3.2). Total grassland area is 3040×10^6 ha, while total forest area is 4050×10^6 ha. There is almost no grassland on histosols, and no forest on aridisols or mollisols. Most of the potentially arable land not yet cultivated is grassland, and the greater part of the grazeable land not yet used is now savannah or forest. A large part of mountain soil is barren land. The soils of humid regions, such as oxisols, alfisols, utisols and most of the inceptisols and entisols, are forested if they are not used for crops or grazing.

3.3.2 Organic Carbon in Major Soils

Descriptions and analyses of more than 400 types of soil were examined for this paper. These studies show that there is great variability in total carbon content in the various types. This variability becomes much smaller when the data are grouped according to soil conditions, particularly when taking into account soil productivity, soil temperature and soil water regimes. The following observations can be made:

(a) The analytical methods used to determine soil carbon often differ;
(b) Soil carbon is not equal to all of the organic matter in a soil, since living plant roots and partly decomposed plant remains are excluded from the analyses;
(c) Real soil humus is the colloidal organic matter in a soil;
(d) Organic material lying on top of the soil (the A_0 or O-horizon, consisting of dead leaves and litter) is not included in the calculation of organic carbon;
(e) All data are expressed in terms of organic carbon, which means that data on organic content have been multiplied by the factor 0.58;
(f) For soils in which soil carbon has been determined to a depth of 1 m or more, soilcarbon content is less than 0.2 per cent below 1 m, and less than 0.1 per cent below 1.5 m. (Some andepts and humods that cover small areas are exceptions);
(g) Soil surface layers (0.20 cm depth) seldom contain more than 5 per cent soil carbon;
(h) The maximum soilcarbon content was 801 t/ha in an hydromorphic volcanic soil;
(i) The minimum soilcarbon content was less than 10 t/ha in a desert soil;
(j) More than half of all the soils studied had a soilcarbon content of less than 150 t/ha;
(k) In most soil orders there is a relatively high soilcarbon content in humid climates, and a relatively low soilcarbon content in hot and dry climates;
(l) Relatively little information is available on soil carbon in forest soils, particularly soils in virgin forests; it is estimated that a secondary forest soil contains 75 per cent of the soilcarbon content of a virgin forest (Nye and Greenland, 1960).

Table 3.3 shows the average organic carbon content of the standard soil orders of the world, but the data in Table 3.3 are not exact averages applicable to any particular country. They are based mainly on differences between the figures for various land-use types. No figures for aridisols and mollisols are given for forestlands, because aridisols are soils usually found in deserts and mollisols are usually found in prairies. Histosols represent the typical organic or peat soils of coastal swamps, which generally have not been reclaimed

Table 3.3 Average organic carbon content of representative soils in relation to major land use (soil carbon in tons per hectare)

Order	Crop land	Grass land	Virgin forest	Secondary forest
Alfisols	80	100	270	200
Aridisols	20	40	—	—
Entisols	60	110	230	170
Histosols	—	—	375	—
Inceptisols	110	140	270	200
Mollisols	130	160	—	—
Oxisols	100	150	240	180
Spodosols	80	90	130	100
Ultisols	80	110	240	180
Vertisols	70	90	190	140
Mountain soils	100	100	200	150

except for some small areas in Western Europe and North America. The figure for histosols (375 t/ha) is based on the assumption of a soil depth of 33 cm (aerated layer), a bulk density of 0.25 and a carbon content of 50 per cent.

3.3.3 Results of Basic Calculations

A calculation has been made of the total soil carbon of each soil order according to land use. Table 3.4 shows the calculation for alfisols. Here, and in all the other calculations, forest area is divided into virgin forest (50 per cent) and secondary forest (50 per cent). Moreover, it is assumed that 'other land' has approximately half of the amount of soil carbon attributed to cropland of the soil order concerned. Similar calculations are made for the other soil orders and for mountain soils.

The results of the calculations are given in Table 3.5. In addition, the percentage of the contribution of each soil order and each land-use type are given, and at the bottom the average soilcarbon content of each land-use type is presented. The total soilcarbon content of all land is 1477×10^{15} g. Kovda (1974) mentions 2400×10^{15} g of humus, which amounts to 1392×10^{15} g of organic carbon. The result of the calculation by Schlesinger (1983) was 1515×10^{15} g, while Woodwell (1978) reports various estimates, ranging from 1000 to 3000×10^{15} g. On the basis of the data in Tables 3.2, 3.3 and 3.5, it is calculated that the average loss of soil carbon after conversion of forest to cropland is 48 per cent, to grassland 28 per cent, and to agricultural land (mixed grassland and cropland) 35 per cent. (The reliability of these results is discussed in a later section.)

Table 3.4 Calculation of soil carbon in alfisols according to major land-use types

Land use (present)	Area (10^6 ha)	Soil carbon in t/ha	Total soil carbon (10^9 t)
Crops	290	80	23.2
Grass	300	100	30.0
Virgin forest	400	270	108.0
Secondary forest	400	200	80.0
Other land	340	40	13.6
Total	1 730		254.8
Land use (prehistoric)			
Virgin forest	1 390	270	375.3
Other land	340	40	13.6
Total	1 730		388.9

Table 3.5 Total soil carbon in various soil orders according to type of land, in gigatons (10^9 t $= 10^{15}$ g)

Order	Crop land	Grass land	Virgin forest	Secondary forest	Other land	Total	Per cent
Alfisols	23.2	30.0	108.0	80.0	13.6	254.8	17.3
Aridisols	0.8	10.4	—	—	21.8	33.0	2.2
Entisols	4.8	22.0	63.3	46.7	7.8	144.6	9.8
Histosols	—	—	18.8	18.7	4.0	41.5	2.8
Inceptisols	16.5	28.0	87.7	65.0	9.4	206.6	14.0
Mollisols	37.7	108.8	—	—	10.4	156.9	10.6
Oxisols	30.0	45.0	54.0	40.5	3.5	173.0	11.7
Spodosols	4.0	13.5	16.3	12.5	4.4	50.7	3.4
Ultisols	10.4	16.5	48.0	36.0	2.0	112.9	7.7
Vertisols	4.2	9.0	4.8	3.5	0.7	22.2	1.5
Mountain soils	11.0	70.0	80.0	60.0	60.0	281.0	19.0
Total	142.6	353.2	480.9	362.9	137.6	1 477.2	100.0
Per cent	9.6	23.9	32.5	25.5	9.3	100.8	
Area (mha)	1 500	3 040	2 025	2 025	4 580	13 170	
Average soil carbon (t/ha)	95	116	237	179	30	112	
Average soil carbon in all cropland and grassland:							109 t/ha
Average soil carbon in all forestland:							208 t/ha

3.4 THE DECLINE OF ORGANIC CARBON IN WORLD SOILS SINCE PREHISTORIC TIMES

It is possible to calculate the organic carbon content of soils in prehistoric times, and consequently the decline in organic carbon content since then, because certain characteristics of the subsoil horizons in soil profiles indicate the original type of vegetation. In prehistoric times there were at least 8590×10^6 ha of forest and natural grassland and 4580×10^6 ha of other land (see Table 3.2). Some 1400×10^6 ha of land were original grassland (mollisols, aridisols and half of the vertisols). The lower part of Table 3.4 shows how the total soil carbon in prehistoric times is calculated. All alfisols present on cropland and grassland once were soils in virgin forests. It is assumed that there has been no change in the carbon content of 'other soils'. The calculation of soil carbon in aridisols, mollisols and vertisols (50 per cent grassland) is based on virgin grassland.

The results of these calculations are presented in Table 3.6, which shows that the total soil carbon in prehistoric times was 2014×10^{15} g, or 537×10^{15} g (26.7 per cent) more than at present. The decline in soil carbon for each order is also shown in Table 3.6.

The average losses of soil carbon have been calculated (see Table 3.5) for the four principal land-use types, taking into account the main soil conditions of the soil orders. It is assumed that the change in land use is distributed over these soil orders proportionally. Another assumption is that any change in the organic matter content of soils that is caused by a change in land use takes place within one year. As mentioned before, it takes at least 10 to 30 years

Table 3.6 Total soil carbon in soil orders during prehistoric times and loss since then

Order	In prehistoric times		Soilcarbon decline		Per cent lost
Soil carbon	(10^9 t)	(per cent)	(10^9 t)	(per cent)	
Alfisols	388.9	19.3	134.1	25.0	34.5
Aridisols	33.8	1.7	0.8	0.1	2.4
Entisols	198.7	9.8	54.1	10.1	27.2
Histosols	41.5	2.1	—	—	—
Inceptisols	279.4	13.9	72.8	13.6	26.1
Mollisols	165.6	8.2	8.7	1.6	5.3
Oxisols	255.5	12.7	82.5	15.4	32.3
Spodosols	62.9	3.1	12.2	2.3	19.4
Ultisols	165.2	8.2	52.3	9.7	31.7
Vertisols	40.6	2.0	18.4	3.4	45.3
Mountain soils	382.0	19.0	101.0	18.8	26.4
Total	2014.1	100.0	536.9	100.0	26.7

before a new soil equilibrium is reached, but since the changes that occur in land use each year are similar, the loss is calculated as if it took place in one year.

The main problem is that global data on changing land use are scarce and unreliable, or at least suspect. Figures that seem to be accurate are often copied from earlier authors who have made rough estimates.

Three estimates of the total annual loss of carbon to the atmosphere are given in the following sections. The first, called realistic, is based on data considered realistic by the author of this paper. The low and high estimates are also based on low and high figures given in the literature.

Table 3.7 shows changes in land use for the period 1964–1974 as given by FAO (1975). In this period irrigated area increased from 194 to 226×10^6 ha, or 3.2×10^6 ha each year. Dudal (1978) mentions an increase in cropland of between 110 and 135×10^6 ha, or approximately 6×10^6 ha each year, for the period 1957–1977.

Table 3.7 Change in world land use in the period 1964–1974 ($\times 10^6$ ha)

Year	Arable land	Grass land	Forest land	Other land	Total land
1964	1 412	2 045	4 062	4 866	13 385
1974	1 507	2 045	4 053	4 787	13 392
	+95	0	−9	−79	+7

SOURCE: FAO (1975) *Production Yearbook.*

Unfortunately, it is not known how much forest is felled, destroyed or transformed into cropland or grassland. Moreover, Table 3.7 does not indicate how much land is misused or used for non-agricultural purposes. Since the amount of grassland has not changed, it is evident that new cropland has been reclaimed from forest or from forest by way of grassland. 'Other land' seems to be reforested. Data on forest areas are especially poor (FAO, 1967), although it is well-known that there is a heavy demand for wood, that forest areas in North America and Europe are increasing, and that large areas of forest in the tropics are being felled and not reforested. The total forest area in the tropics (UNESCO/UNEP/FAO, 1978) is 1915×10^6 ha, of which 1100 are closed forest and 815 open woodlands and shrublands. Approximately 30 per cent of the world's forest area is not exploitable (Wolterson, 1977) because it is inaccessible or needed for protective and regulative functions.

3.4.1 Non-agricultural Land Use

Land is needed every year for new settlements, industries, road and highway construction, recreation, cemeteries and other uses. In Japan the amount of arable and grazing land taken annually for these purposes is 1.1 per cent of the total arable land, in Canada 0.4 to 0.9 per cent, in the Netherlands 0.6 per cent, in Poland 0.5 per cent, in the Unites States 0.5 per cent. In Great Britain, 0.7 per cent of the arable land is lost each year.

During the UN Food Conference in 1974 it was indicated that some 4 to 5×10^6 ha are used for new settlements each year. Another 6 to 7×10^6 ha are taken for other non-agricultural uses. The conference also estimated that some 150×10^6 ha, or 13 per year, would be needed for settlements. In the United States the annual loss of land to non-agricultural use is 1×10^6 ha (Pimentel *et al.*, 1976). At present, 73×10^6 ha of land in the United States are covered by settlements (Kovda, 1977). This author also estimates that by the year 2000 some 25×10^6 ha of farmland will be lost every year. A realistic estimate of the loss of cropland and grassland to non-agricultural use is 0.4 per cent of 4540×10^6 ha, or 18×10^6 ha.

New agricultural land has to be converted from forest in order to compensate for the land lost to non-agricultural uses. Assuming that intensification of agricultural production compensates for the loss of 5×10^6 ha, this means that 13×10^6 ha has to be reclaimed. The conversion of one ha of forest to cropland or grassland releases $208 - 109$ t/ha of soil carbon (Table 3.5). Therefore, the conversion of 13×10^6 ha releases 1287×10^{15} g of soil carbon to the atmosphere.

A low estimate is based on a change to non-agricultural uses of 0.3 per cent of all cropland and grassland, for a total loss of 14×10^6 ha. If it is assumed that intensified agriculture reduces the amount of new agricultural land needed to 10×10^6 ha, the release of soil carbon will amount to 990×10^{15} g.

A high estimate, based on a figure presented by Kovda (1977), is a loss of 25×10^6 ha. Assuming that intensification of agricultural purposes reduces this to 20×10^6 ha, the result would be the release of 1980×10^{15} g of soil carbon to the atmosphere.

These low, realistic, and high estimates are shown in tabular form in Table 3.8.

3.4.1.1 Land Deterioration

FAO (1978) estimated the annual deterioration of agricultural land at 6 to 12×10^6 ha, while Bivas and Bivas (1978) mentions 5 to 7×10^6 ha. Kovda (1974) said that 5 to 6×10^6 ha go out of agricultural production each year. A realistic estimate seems to be 5.3×10^6 ha, or 10 ha per minute. It is assumed here that the intensification of agricultural production compensates for the loss

Table 3.8 Low, realistic and high estimates of the soil carbon released to the atmosphere

Factor	Low estimate		Realistic estimate		High estimate	
	($\times 10^6$ t)	(per cent)	(10^6 t)	(per cent)	($\times 10^6$ t)	(per cent)
Non-agricultural use	990	39	1 287	28	1 980	27
Land deterioration	198	8	297	6	396	5
Shifting cultivation	750	30	1 250	27	1 750	24
Fuel wood, fire	250	10	750	16	1 500	20
Conversion of forest	339	13	1 017	22	1 808	24
Total	2 527	100	4 601	99	7 434	100

of 2.3×10^6 ha, and that the remaining 3×10^6 ha are regained by felling forests. The 3×10^6 ha of forest reclaimed release 208 – 109 t/ha of soil carbon, the total release being 297×10^{12} g. A high estimate, based on the reclamation of 4×10^6 ha from forest, gives 396×10^{12} g of soil carbon released.

Kovda (1974) states that because of erosion the oceans receive 16×10^{15} g of suspended substances annually, with average organic matter of 1 to 3 per cent. If we assume a carbon content of 2 per cent, 160×10^{12} g of soil carbon is transported to the sea annually.

3.4.1.2 Destruction of Forests Due to Shifting Cultivation

According to several authors, up to 250 million people depend for food on shifting cultivation practices. They need at least 400 to 500×10^6 ha of forests for this purpose. If the rotation period is 15 to 20 years (it is usually shorter), these people will cut down 25 to 27×10^6 ha of forest annually. FAO estimates that 30 per cent of all forestland or 1200×10^6 ha, is involved in shifting cultivation, with 103×10^6 ha of this land situated in the Far East (FAO, 1967). Other sources estimate that the area of forest cut down every year for shifting cultivation is 8×10^6 ha in the Far East, 7 in Latin America, 7 in Africa and 2 in Oceania, for a total of 24×10^6 ha. The International Development Resource Centre (IDRC, 1976) estimated that 10×10^6 ha of forest are cut annually because of shifting cultivation, and that 100 ha of unmanaged rain forest in the tropics used for shifting cultivation can feed 30 to 50 people. Flach (1970) also came to the conclusion that in a 12-year rotation period, about two ha of forest are needed per person. But Eckholm (1976) stated that 15 ha per person were needed.

The calculations made below are based on 25×10^6 ha, 15×10^6 ha and 35×10^6 ha for realistic, low and high estimates of the area needed for shifting cultivation. This is partly virgin and partly secondary forest. During three years of cultivation the soil carbon released to the atmosphere is estimated at 50 t/ha, for a decline in organic carbon content of 1.4 per cent in the surface layer.

Calculations made with these data show that a realistic estimate of the soil carbon lost to the atmosphere annually is 1250×10^6 t, a low estimate is 750×10^6 t and a high estimate is 1750×10^6 t.

3.4.2 Destruction of Forest for Use as Fuel or Due to Forest Fire

Approximately 50 per cent of all the forest trees cut down annually in the world are used as fuel. In the tropics (Eckholm, 1976; IDRC, 1976), this figure reaches 80 per cent. More than one-third of the world population depends on wood for fuel. Most authors agree that one ton of wood is used per person per year, which is equivalent to approximately 0.5 cubic meter (m^3) of wood. In the United States in the nineteenth century, three tons of wood per capita were used for cooking and heating (Makhijiana, 1975). At present, wood use is 0.228 m^3 in the United and 0.893 m^3 in South America, where it is highest in the world (IDRC, 1976). Each year some 1000×10^6 m^3 (FAO, 1967) or some 860×10^6 m^3 (IDRC, 1976) of wood are harvested. Assuming that a hectare provides from 86 m^3 to 100 m^3, this means that approximately 10×10^6 ha of forest are cut each year.

There are few data that describe the destruction of forests by forest fire. Bourne (1978) mentions destruction by fire of 1×10^6 ha of forest in southern Para, (Brazil) in 1976. A realistic estimate would be that 5×10^6 ha of forest are destroyed by forest fire each year in the world. The loss of soil carbon during forest fires is about equal to the loss caused by shifting cultivation, 50 t/ha. Therefore, a realistic estimate of the loss caused by forest fires and by the cutting down of trees for fuel is 15×10^6 ha of forest. This would mean the release of 750×10^{12} g C to the atmosphere each year from soil.

3.4.2.1 Conversion of Forest to Cropland and Grassland

Large areas of forest, particularly in the tropics, are converted to grassland or cropland each year. One place where this conversion has taken place on a large scale in recent years is Amazonia (Bourne, 1978), an area of some 600×10^6 ha of virgin tropical forest, of which four-fifths is situated in Brazil. More than 10×10^6 ha of forest were cleared in Amazonia in 1975, mainly for grassland for ranching. Stellingwerf (1969) reported that between 5 and 10×10^6 ha of forest in South America were being cleared annually for agriculture. FAO (1970) reported that 8×10^6 ha of forest in Asia were being transformed every year. Hare (1978) says that 1.5 per cent, or 9×10^6 ha, of the forests in Asia are converted each year. Woodwell (1978) states that FAO data suggest that from 0.6 to 1.5 per cent—i.e., between 24 and 61×10^6 ha of the world's forest—is converted annually. Kovda (1977) concluded that about 20 to 25×10^6 ha of new land would be needed by the year 2000 to compensate for land loss and to meet world food requirements. FAO (1970) estimated that there was an increase of 0.7 per cent of cropland each year. According to Dudal (1978) 25 per cent of all conversion is the result of organized schemes, while 75 per cent is converted spontaneously (see also FAO, *Ceres No. 64*). At the UN World Food Conference in 1974 it was estimated that some 15×10^6 ha will be converted annually in developing countries until 1985.

3.4.3 Total Forest Conversion

A realistic estimate of total forest transformation, based on the figures used in this paper, would therefore seem to be 25×10^6 ha per year. Low and high estimates would be 15 and 40×10^6 ha. Assuming that half of the converted forest is virgin forest and the other half secondary forest, and that the land is used for growing crops, the average decline of soil carbon would be $(208-95) = 113$ t/ha.

The last assumption must be made because the area of the world devoted to grassland has not increased. Thus, if forest is converted to grazing land, grassland is being converted elsewhere to cropland.

A realistic estimate of the loss of soil carbon is therefore

$$(25-16) \times 10^6 \text{ ha} \times 113 \text{ t/ha} = 1017 \times 10^{12} \text{ g}.$$

A low estimate would be

$$(15-12) \times 10^6 \text{ ha} \times 113 \text{ t/ha} = 339 \times 10^{12} \text{ g},$$

and a high estimate would be

$$(40-24) \times 10^6 \text{ ha} \times 113 \text{ t/ha} = 1808 \times 10^{12} \text{ g}.$$

The 1500×10^6 ha of cropland in the world are used to grow food for about four billion people. This means that 0.375 ha is available for each inhabitant of the world. But since the world's population increases about 80 million each year, 30×10^6 ha of new cropland and grassland must be created each year. If we assume that about 20 per cent of the additional need for food is achieved by intensification of farming, this means that 24×10^6 ha of forest has to be cut annually. A total annual clearance of 25×10^6 ha of forest therefore seems to be a realistic estimation.

Although a certain amount of reforestation is occurring, particularly in North America and Europe, it takes many years before the organic carbon content of the reforested soil equals that of the original soil. Nye and Greenland (1960) found that during reforestation in the tropics the annual addition of soil carbon was 1.7 t/ha. There is also a slight increase in soil carbon when land is irrigated, when organic manure is added or when cropping is intensified, but annual addition of soil carbon due to these practices is very small in comparison to the net loss.

3.4.4 The Estimated Total Release of Soil Carbon

The results of the calculations leading to low, realistic and high estimates of the release of soil carbon to the atmosphere are summarized in Table 3.8. The total release is 2.5×10^{15} g for the low estimate, 4.6×10^{15} g for the realistic estimate and 7.4×10^{15} g for the high estimate. The destruction of forest and the conversion of forest to cropland and grassland are the main factors.

3.4.5 Histosols as a Sink for Carbon

Carbon may accumulate in swamps and peatland. The total land area covered by swamps and marshes is estimated by various authors at between 200 and 400×10^6 ha. The FAO/UNESCO soil map shows an area of 240×10^6 ha of histosols (peat soils). The increase in the peat layer is approximately 0.5 mm to 1 mm per year. This means an increase of 5 to 10 m^3 of peat per hectare. If the average bulk density is 0.25 and the carbon is 50 per cent, the total increase is 150 to 300×10^{12} g C. Thus, histosols appear to be absorbing approximately 200×10^{12} g C annually.

3.5 DISCUSSION OF THE RESULTS AND THEIR RELIABILITY

The most important results of this paper are the following:

(1) The total carbon present in the world's soils in prehistoric times, which was 2014×10^{15} g, has declined to 1477×10^{15} g. The net loss of soil carbon since prehistoric times has been 537×10^{15} g, or 27 per cent of the original amount.

(2) The total annual loss of soil carbon is computed to be 4.6×10^{15} g C (realistic), 2.5×10^{15} g (low) and 7.4×10^{15} g (high), these amounts being respectively 0.3 per cent, 0.2 per cent, and 0.5 per cent of the present quantity of soil carbon in the world.

(3) Ninety per cent or more of the annual loss of soil carbon is a consequence of the conversion of forests to grassland and cropland.

(4) The average loss of soil carbon after conversion of forest to cropland is 48 per cent, to grassland 28 per cent, and to agricultural land (mixed cropland and grassland) 35 per cent.

Three methodological aspects of the paper should also be noted:

(1) A somewhat complicated procedure had to be followed to obtain the average soilcarbon content of the various land-use types (Table 3.5) because existing differences related to soil conditions, soil climate and soil productivity had to be taken into account.
(2) Since no exact figures on the amount of land converted annually from forest are available, estimates had to be made.
(3) Since a dynamic model could not be developed because of the lack of accurate data, a bookkeeping model was used.

This study assumes that one hectare of lost agricultural land is always replaced by one hectare of land newly converted from forest. Very often, however, the new land is of lower productivity because the most productive land is already being used and because it is mostly very productive land that is being converted to non-agricultural purposes. This relationship has not been taken into account in this study.

Another factor not taken into account is the oxidation of dead roots in the soil. Also ignored is the organic matter on the surface of mineral soils, even though this matter also contributes to carbon dioxide production. Nor is any attention paid to the decline of the organic matter content of soils in relation to the decrease of soil fertility and consequently to the decrease of agricultural production.

A realistic figure for the amount of soil carbon released annually to the atmosphere is 4.6×10^{15} g. This conclusion, however, means that the recent estimates of 2×10^{15} g (Woodwell, 1978) and 0.8×10^{15} g (Schlesinger, 1983) are too low. Woodwell states that the release of carbon from the decay of soil humus is probably between 0.5 and 5×10^{15} g. The 4.6×10^{15} g calculated in this paper are almost equal to the 5×10^{15} g of organic carbon released annually by the combustion of fossil fuels. According to Schnitzer and Khan (1978), however, the decay of organic soil matter provides the largest carbon dioxide input into the atmosphere.

Another conclusion is that the total amount of soil carbon present in world soils is 1447×10^{15} g, or almost double the 827×10^{15} g of carbon in the biomass growing on world soils. The total quantity of soil carbon is in accordance with an estimate mentioned by Kovda (1974) of 1400×10^{15} g, and with Schlesinger's (1983) calculation of 1515×10^{15} g. According to McKay and Findlay (1978), the carbon content of soils is estimated to be four times the carbon content of land biota. The figure is to be compared with $3000 \pm 500 \times 10^{15}$ g presented by Bolin (1977).

The calculation on the decline of soil carbon since prehistoric times, calculated at 537×10^{15} g (or 27 per cent), is an approximation because part of the land-use type called 'other land' also probably had a forest vegetation with a higher soilcarbon content than at present. It may therefore be that the total loss of soil carbon is higher than calculated. The loss because of the conversion of virgin forest to secondary forest is already 25 per cent, and according to various authors most soils have lost 40 to 50 per cent of their organic matter content within 50 to 75 years after conversion.

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