MASTER

THE ROLE OF ORGANIC SOILS IN THE WORLD CARBON CYCLE — PROBLEM ANALYSIS AND RESEARCH NEEDS

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THE ROLE OF ORGANIC SOILS IN THE WORLD CARBON CYCLE —

PROBLEM DEFINITION AND RESEARCH NEEDS

Edited by
T. V. ARMENTANO

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PREFACE

The continuing rise in the carbon dioxide content of the atmosphere has produced concern that climatic, ecological, and societal effects that will not easily be reversed may occur in the next half-century throughout the world. This prospect has encouraged a critical assessment by the U.S. Department of Energy of the many elements in the global carbon cycle, including man's influence on it.

Because of uncertainty about the dynamics of ecosystem response to human intervention and lack of data on carbon content in many ecosystems, there is disagreement about how much the terrestrial biosphere contributes to carbon accumulation in the atmosphere. However, the role of the terrestrial biosphere in the world carbon budget has been underscored by recent evidence that reduction of the world's biota may be adding at least as much carbon to the atmosphere as is added by combustion of fossil fuels.

The Office of Carbon Dioxide Effects Research and Assessment of the U.S. Department of Energy has funded The Institute of Ecology (TIE) under contract No. 79EV10040.000, to evaluate three of the terrestrial biospheric components that may be important to the world carbon cycle. They are the temperate zone forest (particularly during the past 100 years), freshwater systems subject to eutrophication, and organic soils. The Institute of Ecology has held a workshop on each component, with 10 to 12 researchers on each panel. Each workshop produced data analysis, problem definition, and recommendations for further research.

This report is a summary of the findings and recommendations of the workshop on organic soils, which met in May 1979, at The Institute of Ecology.

Thomas V. Armentano
August, 1979

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EXECUTIVE SUMMARY

The poorly drained organic soils of the world tie up carbon under natural conditions, but when drained, these soils may release large quantities of carbon to the atmosphere.

In May, 1979, The Institute of Ecology held a workshop to determine the role of organic soils in the global carbon cycle and to ascertain their past, present and future significance in world carbon flux. Wetlands ecologists and soil scientists who participated in the workshop examined such topics as "Soils as Sources of Atmospheric CO₂", "Organic Soils", "Primary Production and Growth of Wetlands Ecosystems", and "Management of Peatlands".

The major finding of the workshop is that the organic soils are important in the overall carbon budget. Histosols and Gleysols, the major organic soil deposits of the world, normally sequester organic carbon fixed by plants. They may now be releasing enough carbon to account for nearly 10% of the annual rise in atmospheric content of CO₂.

Other principal findings of the workshop analysis of organic soils and the world carbon cycle include the following:

- Current annual release of carbon from organic soils is estimated to fall within the range of 0.03 to 0.37×10^9 t, a release equivalent to 1.3% to 16% of the annual increase of carbon in the atmosphere. If half of the released carbon remains airborne, organic soils contribute 0.6% to 8.0% of the annual rise in CO₂. Uncertainties in data suggest the actual release could lie outside the range.
- Present annual releases of carbon from the Everglades Agricultural Area in Florida and the Sacramento-San Joaquin Valley in California are estimated at 0.017×10^9 tons. When combined with additional carbon release from other known drainage programs and the possibility of major drainage activity in the tropics, this figure suggests that the lower limit of the world estimate of carbon release from organic soils is too low.
- Annual sequestering of carbon by undrained organic soils has been estimated at about 0.045×10^9 tons. This estimate is based on only a few studies, however, and precision is probably no better than an order of magnitude. This sequestering estimate exceeds the lower limit of the release estimate, but it is unlikely that the current net exchange by organic soils could in fact approach zero.
- Several strategies for peatland management are available, including creation, preservation, functional designation, and use of wetlands for agriculture and energy supply.

Major organic soil data inadequacies exist for total area, pool size, distribution, and depth of organic soils, amount of soil carbon deposits, amount of annual carbon release, extent of drainage activities, and contribution of temperate zone organic soils to the rise of atmospheric carbon in the 19th and 20th centuries.

To reduce uncertainties in data on organic soils, workshop participants recommend a number of research initiatives. These include:

- Critical areas for which further organic soils data are needed should be identified, and a well-defined field measurements program, coupled with remote sensing and vegetation analysis, should be initiated at carefully chosen sites.
- Sites that are undergoing drainage or will be subject to drainage in the near future should be located, and in areas where major interventions are likely, soil samples should be analyzed and permanent benchmarks established to monitor subsidence rates.
- Foreign and U.S. scientists should meet to compile information on peatland development programs and to plan a program of field measurements.
- Remote sensing should be explored as a means of estimating areal changes that result from the spread of agriculture or urbanization of wetlands.
- The effects of pollutants and of changing climate on wetlands should be studied.
- Implications for the world carbon cycle of the large-scale utilization of peat that may result from the current search for reliable energy resources should be examined.

INTRODUCTION

Over the past three decades a continuous rise in atmospheric carbon dioxide concentration has been detected by modern, reliable methods (Keeling et al. 1976). The CO₂ rise has been closely associated with combustion of fossil fuels, which has been increasing regularly since about 1860 (Baes et al. 1977). However, recent reviews of the problem (Bolin 1977, Woodwell et al. 1978) have suggested that additional carbon beyond that from fossil fuels is released into the atmosphere by reduction of the biosphere, principally through destruction of tropical forests. Other potentially significant carbon sources are the poorly drained organic soils of the world, which tie up organic matter under natural conditions. These deposits, if drained, may release large quantities of carbon. Whether sufficient data exist to determine accurately pool sizes of organic soil deposits and their releases of carbon is problematical. The need for acquiring such data depends primarily on whether carbon fluxes between the atmosphere and organic soils are likely to be significant in the world carbon balance.

The Institute of Ecology assembled specialists in soil science and wetlands ecology to examine the significance to the world carbon budget of carbon release from organic soils. The following objectives were addressed in a workshop held in May, 1979:

1. Review and analysis of available data on carbon in organic soils from the past century to the present
2. Assessment of the probable flux of carbon to and from organic soils in the near future
3. Identification of major data inadequacies which preclude reliable analysis of the principal processes influencing carbon flux in organic soils
4. Proposal of research initiatives which could improve understanding of organic deposits in relation to the carbon cycle within a time frame of two to four years

SOILS AS SOURCES OF ATMOSPHERIC CO₂*

Soil carbon is a major component of the world carbon cycle, exceeding by up to three times the quantity of carbon in the world biota or in the atmosphere (Bohn 1976). Estimates of the current and past transfer of carbon from soils to the atmosphere vary widely (Table 1) and seldom distinguish organic soils from soils as a whole. Estimates of the release of carbon to the atmosphere resulting from human intervention over the last century have been based principally on carbon isotope analyses, which

*Based on analysis and presentation by T. V. Armentano

leave little basis for evaluating the importance of extensive drainage programs in biospheric carbon release. For soils as a whole, estimates of cumulative carbon release differ over two orders of magnitude (Table 1). Estimates of carbon released from soils alone, or as components of total biospheric flux (Table 1) are sufficiently large to suggest that an important fraction of the carbon added to the atmosphere over the last century originated in the biosphere, principally in soils and in forest trees. Wilson (1978), for example, concludes that clearing and ploughing of mid-continental rich grassland and organic soils of North America, Europe, New Zealand and South Africa between 1860 and 1890 released 110×10^9 metric tons of carbon -- enough to raise the atmospheric CO_2 concentration by 10% and still allow for 50% absorption by the oceans. This increment would have accounted for most of the CO_2 rise over the 30 years when fossil fuel combustion was relatively small.

Direct measures of the loss in carbon from long-term cultivation have been made principally in better-drained soils (Table 2). Paul (1976) estimates a carbon loss ranging from 2.76 to 6.6 $\text{kg} \cdot \text{m}^{-2}$ for brown and black chernozems over the past 60 to 75 years. These losses may be representative of the 2.83×10^7 ha of prairie under cultivation in western Canada. In this area, if brown and black chernozems were equally distributed the total carbon released would equal 1.3×10^9 t -- about 1.5% of the CO_2 increase in the atmosphere since a century ago (85×10^9 t C, equivalent to a 40 ppm rise in CO_2 concentration). If ten times that amount were released from other cultivated soils in the temperate zone, the total would be 15% of the total rise in CO_2 concentration, less than one-eighth the release suggested by Wilson (1978). Since many organic soils, like some upland soils, probably have released greater quantities of carbon than the chernozems (Table 2), the aggregate loss from soil cultivation would be somewhat higher, clearly a significant fraction of the rise in atmospheric CO_2 , although less than Wilson's estimate. The proportion of carbon released from organic soils alone cannot be calculated without further analysis of the historical trends in organic soil cultivation and carbon release.

Current estimates of the annual release of carbon from soils range from 0.1 to 5.0×10^9 t (Table 1), but these figures are not strictly comparable since the larger figure includes timber harvest. Furthermore, estimates by Bolin (1977) and Woodwell *et al.* (1978) emphasize the temperate zone, while Hampicke (1979) thinks losses are greatest in the tropics. In each of these cases, the basis for the estimate is a weak one, and the authors recognize that higher fluxes are quite possible. Estimates of the cumulative carbon flux from soils range over two orders of magnitude (Table 1). Only part of this variation comes from the differences in the time periods under consideration. Data uncertainties are clearly large, and refinement is needed.

Estimates of the cumulative flux of carbon from the biosphere range from 70 to 208×10^9 t C over approximately a 100-year period, beginning in 1850 (Table 1). Most of these results derive from $^{13}\text{C}/^{12}\text{C}$ isotope analysis, the only method which gives a cumulative total flux of carbon. Estimates

Table 1. Estimates of total release of carbon since the 19th century and the current annual rates of carbon release from soils and from the biosphere.

Release of Carbon from Soils	10 ⁹ t C		Comments
	Cumulative Release	Current Annual Release	
Revelle and Munk (1977)	25		1860 - 1970
Bolin (1977)	10 - 40	0.1 - 0.5	Cumulative release since early 19th century
Loomis (1977)	1 - 3		1840 - 1950; U.S. prairies
Wilson (1978)	110		1860 - 1890
Bohn (1978)		1 - 2	
Woodwell <u>et al.</u> (1978)		0.5 - 5.0	Includes timber harvest
Hampicke (1979)		0.6	Mostly in tropics
Schlesinger (1979)		0.8	
Release of Carbon from the Biosphere			
Revelle and Munk (1977)	72		1860 - 1970; Based on USDA/FAO data
Adams <u>et al.</u> (1977)		0.4 - 4.0	Based on wood consumption
Bolin (1977)		0.4 - 1.6	Net transfer
Stuiver (1978)	120		1850 - 1950; Based on ¹³ C/ ¹² C
Woodwell <u>et al.</u> (1978)		7.8 (2-18)	Net transfer; Mostly in tropics
Wagener (1979)	208		1850 - 1975; Based on ¹³ C/ ¹² C
Freyer (1979)	70	3 ± 2	1850 - 1974; Based on ¹³ C/ ¹² C
Chan <u>et al.</u> (1979)	121	2.6 - 2.9	Computer model simulation
Hampicke (1979)		1.5 - 4.5	Mostly in tropics

Table 2. A partial survey of carbon losses in soils subject to long-term cultivation.

Site	Soil Type	Length of Cultivation (yr)	Loss of Carbon kg m ⁻²	Source
Saskatchewan	Chernozem (brown)	60 - 75	2.75 (top 30 cm)*	Paul (1976)
Saskatchewan	Chernozem (black)	60 - 75	6.6 (top 30 cm)	Paul (1976)
Georgia piedmont	Sandy loam	25	2.24 (top 15 cm)	Giddens (1957)
Missouri prairie	Silt loam	60	1.8 (top 18 cm)	Jenny (1941)
USSR (European)	Gray forest	100	10.2 (top 1 m)	Rubilin & Dolotov (1967)
USSR (trans-Caucasus)	Podzolic	?	9.9 (top 1 m)	Tyurin in Rubilin & Dolotov (1967)
USSR	Sod-podzolic (unmanured)	48	52% of virgin humus	Kononova (1966)
USSR	Sod-podzolic (manured)	48	52% of virgin humus	Kononova (1966)
USSR (steppe)	Chernozem (fallowed)	10 - 12	4 - 6 (top 1 m)	Lazarev in Rubilin & Dolotov (1967)

* Depth of soil investigated.

of the current annual rate of carbon loss from the biosphere as a whole range from 0.4 to as high as 18×10^9 t C (Table 1). Comparing estimates of the carbon release for the biosphere with that for soils suggests that soils may be contributing 25% or more of the annual biospheric carbon release (Table 1), but uncertainties are at the level of an order of magnitude. Similar uncertainty characterizes estimates of cumulative releases, which suggest that soils could have contributed up to one-half of the total release from the biosphere since the mid-19th century.

PRESENT CARBON POOL SIZES IN THE WORLD'S SOILS*

The role of organic soils in the carbon cycle depends principally on the rates of loss or gain of carbon, not on pool sizes. Since direct measures of carbon exchange are available only from a few sites, however, they must be estimated by combining information on pool sizes, geographic distribution and the extent of human intervention. Because organic soils data are not usually summarized separately from data on soils as a whole, data on the entire soil carbon pool must be examined.

Estimates of the organic carbon pool of the world's soils (including well drained and poorly drained organic soils) have been made in at least two different ways. Some estimates have been based on soils maps such as those by the United Nations Food and Agricultural Organization (FAO) or the U.S. Soil Conservation Service (Table 3). Other estimates have been made by summarizing available data for various ecosystem types (Table 4). Uncertainties in both approaches result in a wide range in estimates. The reliability of soil mapping data varies greatly between countries, with fewest data available for the tropics, but even for the comparatively well-studied North American continent, considerable disagreement exists (Table 3). Mapping data errors may be large, but they are difficult to calculate. Bohn (1976) estimated that the error of his world soil assessment was $\pm 500 \times 10^{15}$ g, or 17% of the mean.

Difficulties in the ecosystem or biome-type approach arise principally from the necessity of extrapolating data from a small number of studies to a large geographic area. For example, estimates by Schlesinger (1977) of the soil carbon in the arctic and alpine tundras of the world were based on 31 sampling stations and 11 references; in the boreal forest, 21 stations and 7 references; and in the temperate grasslands, 18 stations and 6 references. The coefficient of variation of the estimates for the boreal forest was 53%, and it was even higher for swamps and marshes and for the tundra.

Schlesinger (1979) has recently revised his estimate of world soil carbon, based on new data (Table 4). The revised estimate, based on an addition of 35 stations to the compilation of Schlesinger (1977), is 1515×10^9 t of carbon, 4% higher than the previous estimate. No information is provided on the variability of the new data. For the boreal forest,

*This section was adapted from an analysis and presentation by T. V. Armentano.

Table 3. Quantities of organic carbon accumulation in the soil, based on FAO-UNESCO data and maps. Data are in 10^9 tons of carbon.

Continents	Bohn (1976)*	Ajtay et al. (1979)*
North America	665	248
U.S.A.		135
Central America (incl. Mexico)		48
South America	301	306
Africa		320
Asia		541
Europe	1980	74
USSR		440
Oceania		93
Greenland and Antarctica		?
Terrestrial total	2946	2205*

*Reported in Ajtay et al. (1979) as 2070×10^9 tons.

Table 4. Two recent estimates of the carbon content of soils in ecosystems of the world. Areas are given in 10^8 ha and carbon content in 10^9 tons.

Ecosystem Type	(Ajtay et al. (1979))		Schlesinger (1979)	
	Area	Total Carbon	Area	Total Carbon
Tropical forests	14.8	122.9	24.5	288
Temperate forests	6	72	12	161
Boreal forests	9	135	12	247
Temperate woodland	2		8.5	59
Chaparral	2.5	72		
Forest plantation	1.5			
Savanna derived	12	180		
Savanna thorn	10.5	84		
Tropical grassland			15	63
Temperate grassland, dry	7.5	225		
Temperate grassland, wet	5	70	9	170
Tundra polar desert, high arctic	5.1	33.2		
Tundra polar desert, low arctic	4.4	88	8	163
Desert, semidesert	21	168	18	104
Extreme desert	9	22.5	24	4
Perpetual ice	15.5			
Swamp, Marshes	2	60		
Bog, Peatland	1.5	165 ⁽¹⁾	2	145
Lake and stream	2			
Cultivated land	16	128	14	111
Human area	<u>2</u>	<u>10</u>	<u> </u>	<u> </u>
Total terrestrial	149.3	1635.6	147	1515

(1) Calculated from data of Moore and Bellamy (1975).

the only ecosystem for which a breakdown of the data is given, the number of references for the new estimate is 13, and the number of sampling stations is 34 or more (one reference did not report the number of sites).

Estimates based on ecosystem types are considerably lower than those based on mapping information (Tables 3 and 4). The estimates of Ajtay *et al.* (1979) and Schlesinger (1979) are within 8%, but differences are much greater for certain ecosystem types, partly because of disagreement on areal extent. Differences are greatest in the tropical forest estimates, where the discrepancy is over 100 percent. Schlesinger's boreal forest estimate is 83% larger than Ajtay's, while his estimate for wetlands soils is 54% smaller (Table 4). The estimate for boreal deposits by Schlesinger is higher, apparently because he includes peatlands within the boreal forest (Schlesinger 1979). There is agreement, nevertheless, that approximately 25% of the world soil carbon pool may be found in boreal and wetland ecosystems and another 10% in the tundra. Each of these ecosystems contains substantial deposits of wet organic soils.

A difficulty with both mapping and ecosystem-type approaches is the lack of data on depth of the deposits, which is of special significance in organic soils. Bohn's (1976) estimates are based on a depth of one meter. The literature survey upon which Schlesinger (1977) based his estimates shows wide variation in the depth of the deposits sampled, with most less than one meter. In most wetlands, deposits exceed one meter in depth, and some, such as those of the San Joaquin Valley in California, may reach a depth of six meters. Clearly, estimates of pool size in wetlands would be much larger if the entire depth of the organic deposit were included. A second uncertainty is whether the estimates by Ajtay *et al.* and Schlesinger include salt marsh and estuarine peat and sediment, which total about 178×10^6 ha in area (Woodwell, Rich and Hall 1973). The carbon in sediments of lakes, ponds, rivers and reservoirs has apparently not been estimated.

ORGANIC SOILS

The major organic deposits of the world can be classified according to the FAO soil classification and U. S. Soil Taxonomy (Soil Survey Staff, 1974) systems as either Histosols, of which peat deposits are one type, or Gleysols. The organic soil material of Histosols, which is derived from plant residues, must contain at least 12 to 18% organic carbon by weight, and exceed 30-40 cm in depth. Gleysols are mineral soils with gleyed horizons. Histic Gleysols and Humic Gleysols, two of the nine subdivisions of Gleysols, may be high in organic carbon but contain less than the minimum for Histosols.

Total Areas of Organic Soil Deposits*

Estimates of the areas of Histosols and Gleysols found throughout the world based upon the world soils map of the FAO (1971-1978) (map scale = 1:5,000,000) are presented in Table 5. Bohn considers these estimates a partial update of his estimate of 431×10^6 ha for world Histosols (Bohn 1976).

The major distribution of Gleysols is found from latitude 20° to 40° N in southern Asia, the U.S., China and the USSR, and around the equator in South America and Africa. Because of a paucity of data, error bounds for the estimate of Gleysol areas is not given, but is probably no better than 50% of the mean. Gleysols of Southeast Asia and other areas that have been cultivated for many decades have probably already reached their steady state organic carbon levels, but in the future it is possible that new inroads into these soils may occur, resulting in greater releases of carbon than at present.

Uncertainties in the extent of Histosols throughout the world result in estimates which differ by nearly 100% (Table 5). Major uncertainties concern the extent of Histosols in Southeast Asia, Canada, Europe, and the USSR. A widely cited estimate of peatland resources may be 40% too low (Table 6). Comparison with soils data summarized by ecosystem type (Table 4) suggests that estimates in Table 5 may be low. According to Ajtay *et al.* (1979), bog and peatland, swamp and marsh, and wet temperate grasslands contain large areas of Histosols and Gleysols (Table 4). The total area of these categories is 850×10^6 ha, which exceeds the range of 537 to 759×10^6 ha for the areal estimate of Histosols and Gleysols in Table 5. Because of the uncertainty connected with the Gleysol estimate, the present range of mapped data estimates should be perhaps 530 to 900×10^6 ha. The estimates of Ajtay *et al.* suggest that the mapped estimate could be higher than, or near the maximum of, the suggested range. Although some wet grasslands may not have Histosols or Gleysols, other ecosystem categories, such as taiga, tundra, and certain tropical ecosystems, contain additional organic deposits.

Utilization of Gleysols**

Estimates of carbon release from Gleysols is hampered by inadequate data on pool sizes and the extent of drainage activities, present and past. Nevertheless, the approximate present annual release of carbon from Gleysols can be estimated with the following assumptions: that one percent of the world's Gleysols (3×10^6 ha) are being converted to agriculture by drainage, that carbon loss is $0.5 \text{ kg} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$, and that drainage reduces organic carbon to 50% of the original carbon content. Annual release of carbon

*This section was adapted from an analysis and presentation by H. Bohn and D. Franzmeier.

**Based on an analysis and presentation by H. Bohn, D. Franzmeier and C. C. Delwiche.

Table 5. Estimates of the major areas of Histosols and Gleysols in the world. Data based on a presentation by H. Bohn of the University of Arizona. Histosols are defined as containing over 15% organic carbon by weight. Gleysols are defined as organic soils containing less than 15% organic carbon on a wet-weight basis.

Latitude	Region	Area (in 10 ⁶ ha)	
		Histosols	Gleysols
40°-50° S	Chile	3 - 6	
20°-30° S	South America		19
10°-20° S	Zambia		3
0°-10° S	Brazil, Zaire		54
0°-10° N	Indonesia (coastal swamps)	25 - 50	
	Orinoco Basin, Nigeria, Sudan		34
10°-20° N	Central America (coastal swamps)	2	
	Africa, Indochina		46
20°-30° N	United States (coastal swamps)	2	
	Burma, Bangladesh, United States		47
30°-40° N	Himalayas	7 - 14	
	China, USSR		70
40°-50° N	United States, China, USSR		22
50°-60° N	Canada, Europe, USSR	80 - 160	
	Europe		16
60°-70° N	Canada, USSR	90 - 180	
70°-80° N	USSR	17 - 34	
Total		226 - 448	311

Table 6. Two estimates of the world's peat resources (in 10^6 ha).

Country	Moore & Bellamy (1975)	Farnham ²
USSR	71.5	150.0
Canada	129.5	112.0
United States	7.5	21.0
Finland	10.0	9.7
Sweden	1.5	7.8
East/West Germany	1.6	5.2
Great Britain/Ireland	1.8	5.2
Poland	1.5	3.4
Norway	3.0	3.0
Indonesia/Malaysia	0.7 ¹	2.4
All others	1.9	2.2
Total	230.5	321.9

¹ Indonesia only.

² Based on a presentation by R. Farnham of the University of Minnesota.

would then equal a world total of $0.015 \times 10^9 \text{ t yr}^{-1}$. This estimate of carbon loss may be somewhat high, because the 1% annual drainage rate could exist only over the short term during the period of rapid drainage. Delwiche independently estimated an annual loss of carbon of $0.01 \times 10^9 \text{ t yr}^{-1}$, by assuming that 10^6 ha of Gleysols are exposed to drainage per decade and that oxidation releases $10 \text{ kg m}^{-2} \text{ C}$. In the United States and Europe, where there is adequate capital and advanced technology, this rate of change could occur. In Africa and in Southeast Asia, where land utilization is more stable and follows population pressure, rather than economic fluctuations, utilization of Gleysols is probably nearly complete. In Southeast Asia, Gleysols are attractive for rice, because the fine soil texture simplifies water control. Recently increasing interest in dry-land rice growing may reflect the lack of availability of new gleysol soils.

Utilization of Histosols*

World Trends

No more than 15% to 25% (i.e., about $50 \text{ to } 70 \times 10^6 \text{ ha}$) of the world's Histosols are found in climates that are suitable for agriculture. On an average, approximately 10% of these lands, or $5 \text{ to } 7 \times 10^6 \text{ ha}$, are now being farmed. As a maximum, no more than 50%, or $25 \text{ to } 35 \times 10^6 \text{ ha}$, could be developed for agriculture. The release of carbon from Histosols that are now being cultivated or could feasibly be cultivated in the future would then vary from about $0.05 \text{ to } 0.35 \times 10^9 \text{ t yr}^{-1}$ (assuming an annual release of $10 \text{ t ha}^{-1} \text{ yr}^{-1}$), but may be only one-half or one-fourth of this estimate. These carbon output rates would be relatively constant until the Histosols were consumed by oxidation.

A second estimate of carbon release from Histosols assumes that annual rate of oxidation of organic matter destroys 1 to 3 cm of soil, that bulk density of Histosols is 0.15 gm cm^{-3} , and that one-half of the organic matter is composed of organic carbon. Under these conditions the evolution of carbon would range from $0.02 \text{ to } 0.07 \times 10^9 \text{ t yr}^{-1}$. Peatlands that are not adequately drained for crop production may be subsiding at rates one order of magnitude less than the 1 to 3 cm estimate given. The area of incompletely drained peatlands, and the reliability of the estimate of subsidence rates and carbon release, are not known. Delwiche (this workshop) calculated that $0.1 \times 10^9 \text{ t C}$ may be released annually from $2 \times 10^6 \text{ ha}$ of Histosols subsiding at an annual rate of 5 cm. He estimated the precision of the area determination to be about 20% of the mean; of the oxidation rate, 30%, and of the extent of exposure of Histosols, 50%. Undertainty about Gleysols is of the same order.

Under nearly ideal laboratory conditions, decomposition rates for a Canadian histosol varied from less than 50 ppm to 1200 ppm of carbon per day. At a rate of 200 ppm of carbon per day, decomposition in the top

*Based on analyses and presentations by J. Duxbury, R. Farnham, H. Bohn and D. Franzmeier.

20 cm of the peat soil would produce a subsidence rate of 1.5 cm yr^{-1} , if all the loss in volume results from carbon loss. For soils with bulk densities ranging from 0.1 to 0.4 g cm^{-3} , the amount of carbon evolved annually would vary from 5.8 to 23.4 t ha^{-1} . At this rate, drainage of $2 \times 10^6 \text{ ha}$ of organic soils would release 0.01 to $0.05 \times 10^9 \text{ t C}$, within the range of estimates previously presented in this report. Although laboratory rates are usually higher than field rates, these laboratory estimates are relatively low because they are based on soils with a frost-free period of 120 days.

Less is known about the massive peat deposits in North and South America (Guayana, Surinam), eastern Indonesia (Borneo and Sumatra), and Southeast Asia than for other areas. Neither the total extent of these deposits nor their depth over large areas is known, so the total size of the pools cannot be estimated. Although efforts are underway to drain these deposits, the extent of these efforts and their success are unknown. However, the potential for large releases of carbon from these deposits in the near future cannot be discounted.

For lands above latitude 50° N , probably no more than 0.1% of the Histosols (principally in Canada, USSR, and Alaska) are drained. Most of the drainage is for fuel harvesting, which does not reclaim the soils sufficiently for row crop production. Thus, carbon losses would be expected to be lower than in soils supporting row crops. In the continental United States, Europe and Scandinavia, about 5% of the histosol areas are adequately drained for row crop production. In the tropics, little of the histosol areas are used by man, but 5% could be used for rice growing and grazing.

The total drained land north of latitude 50° N is estimated to be $4 \times 10^5 \text{ ha}$, and the total drained land south of latitude 50° N is estimated to be $2.5 \times 10^6 \text{ ha}$, for a total of about $3 \times 10^6 \text{ ha}$. Because of the difficulty in reclaiming Histosols, most of those with potential for development have already been drained and are being utilized. Major problems in reclaiming these soils are as follows:

1. high cost of drainage and maintenance
2. high probability of flooding
3. low nutrient content of the soils
4. above latitude 40° N , unfavorable climate for crops
5. high, specific heat capacity of soils when wet, and very low heat conductivity when dry
6. high sulfide content in many coastal organic soils
7. generally high initial subsidence, accentuating drainage problems
8. high cost of management of local water regimes

Subsidence and Carbon Release to the Atmosphere*

Subsidence or shrinkage of organic soils usually accompanies drainage. It may be caused by any of several factors, including compaction, wind

*Based on a presentation and analysis by S. P. Mathur, L. H. Allen and J. Duxbury.

erosion, fire, and desiccation, but the only process significant in the carbon cycle is biochemical oxidation. Because subsidence is easily measured and of practical importance for agriculture, long-term data sets are available that can provide insight into carbon release over many decades. Subsidence data alone, however, cannot be used to estimate carbon release. The rate of subsidence depends mainly on temperature, water content, and the physical nature of soil material, and depth to the water table. Subsidence rates have been found to vary from less than 1 to more than 8 cm per year (Table 7).

Subsidence of peat soils can also be caused by changes in bulk density, which must be considered in calculating losses of carbon. For example, the bulk density of sphagnum peat changes from about 0.05 to 0.2 g cm³ as it is humified. The initial loss in volume is from shrinkage caused by drying; as sedge peat humifies, its bulk density changes from 0.1 to 0.4 g cm³ without a substantial change in percent carbon content. Generally, the major changes in bulk density occur in the top 20 or 30 cm of peat, an interval in which variation may be high and affect calculations of carbon loss (Figure 1).

The oxidation component of subsidence varies widely with climate; it is generally a smaller component of peat subsidence in cool climates than in temperate and tropical climates. Stephens (1974) reports that Russian studies show that only 13% to 14% of the total subsidence of organic soils near Minsk was caused by oxidation. The major factors were compaction and desiccation. By comparison, in the Netherlands, oxidation accounted for 20% of subsidence, and in the Everglades up to 78% of total subsidence results from oxidation.

The Everglades Agricultural Area and the San Joaquin Delta

The Everglades Agricultural Area in Florida and the Sacramento-San Joaquin Delta in California are prime farming areas developed on Histosols. These sites, subject to extensive and continuing drainage for more than 50 years, represent the best available sources of information on long-term response of peat surface elevation to water table withdrawal.

In the Everglades Agricultural Area south of Lake Okeechobee (3.1 x 10⁵ ha), drainage of freshwater peat was begun in 1912. Subsidence reached 1.8 m by 1950 (Stephens and Johnson 1951), and about 3.3 m by 1970 (Stephens 1974). By the year 2000, large areas are expected to be reduced to 0.3 to 0.6 m of organic soil over a limestone base, a depth of soil too shallow for crops such as sugarcane and vegetables. Subsidence rates generally decreased exponentially over the first few years and then leveled off to a lower rate that typically varied from 1 to 3 cm per year. Major changes in bulk density have also occurred, and it can be assumed that major losses of carbon also occur during periods of major subsidence. The bulk density of the Everglades soils is about 0.23, the soil organic matter content is about 88%, and the carbon content of the organic matter averages 56%. At a subsidence rate of 2.54 cm yr⁻¹, Everglades peat would release 0.009 x 10⁹ t C yr⁻¹, about 0.18% of world fossil fuel emissions.

Table 7. Measured rates of subsidence of organic soils for specific sites in different areas. Data from survey by L. H. Allen and J. Duxbury.

Location of Site	Annual Subsidence Rate (cm yr ⁻¹)	Cumulative Subsidence (cm)	Time Period (yr)	Average Depth to Watertable (cm)
California Delta (2 sites)	2.5 - 8.2	152 - 244	25	
Louisiana (estimated)	1.0 - 5.0			
Michigan	1.2 - 2.5	7.6 - 15	5	
New York	2.5	150	60	90
Indiana	1.2 - 2.5	7.6 - 15	6	
Florida Everglades (2 sites)	2.7 2.7 - 4.2	147 19 - 29	54 7	90 60
Netherlands (2 sites)	0.7 1.0 - 1.7	70 6 - 10	100 6	10 - 20 50
Ireland	1.8			90
Norway	2.5	152	65	
England	0.5 - 5.0	325 (by 1932) 348 (by 1951)	84 103	
Israel	10			
USSR (Minsk bog)	2.1	100	47

Figure 1. Depth profile of bulk density for Everglades peat. A similar profile can be found in many northern peat areas such as in New York. Data from J. Duxbury.

The amount of carbon lost from the entire Florida Everglades, which contain over 8×10^5 ha, the largest area of organic soils in the world (Shih, et al. 1979) is not known. Water table withdrawal and fires may have converted the Everglades from a carbon sink into a net source of carbon dioxide. Although sediments are not as deep here as in the agricultural zone, the areal extent is much greater, and the total pool of carbon in the sediments may be larger in the sawgrass area.

In the San Joaquin Valley in California, which in 1922 was about 0.6 m below sea level, the peat surface had sunk by 1950 to more than 3 m below sea level, an average of 7.6 cm of subsidence per year (Weir 1950). The current level of peat surface is about 6 m below sea level. About 0.008×10^9 t C is released annually from the Sacramento-San Joaquin Delta, according to Allen, who assumed a subsidence rate of 7.6 cm yr and an area of 10^5 hectares. The total carbon release from the Everglades Agricultural Area and the San Joaquin Delta is 0.017×10^9 t annually - an estimate that is 5% to 85% of the carbon release (0.02 to 0.35×10^9 t) given for the world's Histosols previously in this report. There is considerable uncertainty as to the reliability of both global and site-specific estimates, but the latter are based on better data. Since carbon is being released from Histosols other than those in Florida and California, release from world Histosols is probably much above the lower limit of the estimate just given. A more intensive synthesis of existing data might refine present estimates, but new data are needed for areas of major deposits, particularly in the tropics. Because oxidation rates and other chemical processes are directly proportional to temperature, losses of carbon from wetland soils in subtropical and tropical regions of the world may be quite high, but data are lacking for most of these sites except the Everglades.

PRIMARY PRODUCTION AND GROWTH OF WETLANDS ECOSYSTEMS*

In the absence of intervention by man, wetlands function as natural sinks for carbon synthesized by primary production of green plants. Short-term studies of primary production of wetlands indicate that wetlands are highly productive (Table 8), with about 10% of net primary production converted to peat stored in the sediments underlying the vegetation (Reader and Stewart 1972). In the absence of fire, as much as 30% of production may be converted to peat in northern peatlands (calculated from Richardson 1978). Long-term vertical accretion can be estimated from carbon 14 profiles, which provide a mean over a period of time ranging from thousands to tens of thousands of years (Table 9).

Such a long-term mean must be interpreted as a net accretion, with some losses having occurred during the interval. Estimates range from up to 20 cm vertical accretion over 100 years in the Everglades to 2 cm in

*Based on an analysis by C. J. Richardson, L. H. Allen and R. Farnham.

Table 8. A comparison of available data on net productivity of wetlands and some productive upland ecosystems. Data are from a literature summarization by C. J. Richardson (1979).

Ecosystem Type	Net Productivity (t ha ⁻¹ yr ⁻¹)	Number of Sites Studied
	Total of Above and Below Ground	
Cattail Marsh	27.4 ± 6.7	(5)
Reed Type Marsh ¹	21.0 ± 5.8	(5)
Papyrus Marsh	90 - 150	(1)
Fresh Water Tidal	16 ± 2	(2)
Carex Marsh	10.4 ± 1.0	(5)
Bogs, Fens and Muskeg	9.3 ± 4.6	(9)
Grasslands in U. S.	5.1 ± 1.5	(9)
Bog Forest	6.7	(1)
	Above Ground Only	
Swamp Forests	10.5 ± 3.3	(6)
Boreal Conifer Forests	9.0 ± 3.5	(19)
Pine Forests	10.4 ± 5.7	(15)
Temperate Coniferous	14.9 ± 9.0	(5)
Tropical Rainforest	16.5 - 28.2	(2)
Deciduous Broad-leaf	10.2 ± 2.3	(57)

1. C. Papyrus not included.

Table 9. Retrospective dating of peat deposits in Washington (Puget Sound area) and Florida (Everglades). Dates of deposits were determined by ^{14}C techniques, and in the case of Washington by comparison with ash from the eruption of Glacier Peak about 6700 years before the present. Data from Rigg and Gould (1957) and MacDowell, Stephens and Stewart (1969).

Area	Thickness of Peat (m)			Rate of Sedimentation ($\text{cm } 10^2 \text{ yr}^{-1}$)		
	Total Column	Dating Interval		Total Column	Dating Interval	
		11900-6700 BP	6700 BP-Present		11900-6700 BP	6700 BP-Present
Puget Sound (151 bogs)	7.3	3.0	4.3	6.2	5.9	6.4
		3500-1200 BP	1200-65 BP		3500-1200 BP	1200-65 BP
Everglades	3.65	1.37	2.28	8.4	7.3	20.0

far northern peatlands (Table 10), although other reports suggest that 10 cm per century is average (Bohn 1978). For the most part, differences in reported net productivity rates (Table 8) are smaller than are differences in reported rates of carbon accumulation (Table 10), when compared over a wide range of sites. One explanation of these differences is that other processes than net productivity may be overriding factors in determining peat accumulation rates. Such characteristics as hydrology, topography, substrate chemistry, and stage in vegetation succession can be important determinants of wetland functioning in general (see Good *et al.* 1978, Aandahl *et al.* 1974), and may directly influence carbon accumulation rates. During the time interval approximated by carbon 14 dating, sea level rise may have influenced the rate of carbon deposition along coastal areas, but since it still removes carbon from the atmosphere, the process can be interpreted as a carbon sink.

Lateral growth of peatlands, or paludification, may be an important process in northern peatlands. Western Siberia has about 7.9×10^6 ha of peatlands that were formed 10,000 to 12,000 years ago (Neishtadt 1977). About 50% of the West Siberian Plain is occupied by mires. There has been net growth of these bogs and mires over the last 8,000 years, during the Holocene period, with an annual increase in bog area of 10^4 hectares during this period. Neishtadt considers this rate of paludification to be much greater than in any other area of the world, but comparable spreading of peatlands may also be occurring in northern Canada and Alaska. In contrast, more tundra peat may be exposed to oxidation because of isostatic rebound and the melting of permafrost. Data are not available to make even a general assessment of the rate of peat expansion or peat oxidation in the northern circumboreal areas, but paludification could be functioning as a large carbon sink, offsetting carbon release from drainage of organic soils or clearing of upland soils.

Thus far, there has been little drainage of the peatlands of western Siberia, although there has been some support in Russia for their economic development. Drainage of 10^3 to 10^4 ha or more of wet areas in northwestern and central regions of the European part of the USSR has occurred, but the total release of carbon cannot be estimated, since the depth of the deposits and the subsidence and oxidation rates are not available. Most of the loss of carbon from these developed areas in European USSR has probably already occurred, and the major changes in the Russian peatlands are occurring in Siberia where, in the absence of major drainage schemes, paludification is probably causing a net carbon sink.

Richardson and Allen compiled some of the data available for natural peatland accumulation rates to provide the basis for an initial approximation of carbon storage rates for the world's peatlands (Table 10). Carbon accumulation was weighted for lower rates in northern peatlands by assuming a world average of $100 \text{ kg ha}^{-1} \text{ yr}^{-1}$. For a peatland area of 4.5×10^8 ha, about 0.045×10^9 t C would be added to peatlands annually. The uncertainties in total area of organic soils (Table 5) mean that the accumulation

Table 10. Estimates of carbon accumulation rates for some natural peatlands.
Calculations by C. J. Richardson and L. H. Allen.

Peatland System	Bulk Density g cm ⁻³	Accretion Rate cm yr ⁻¹	% Carbon Content of Biomass	Carbon Accumulation Rate in Peat kg ha ⁻¹ yr ⁻¹
Florida Everglades:				
3500-1200 BP	0.15	0.07	50	525
1200-65 BP	0.15	0.20	50	1500
Minnesota Peatlands	0.05	0.15	50	333
Northwest Territories	0.05	0.02	50	50
Washington State	0.15	0.065	50	500
Manitoba (combined average)			40	372
Michigan	0.13		40	110
Cattail Marsh - average for 41°-45° N. Latitude	0.15		40	996

estimate may be too high if accumulation only in Histosols is considered. Another source of error, probably of smaller magnitude, is the loss of organic carbon from swamps. Mulholland and Kuenzler (1979) have shown the amount of organic carbon in streams draining swamps is severalfold higher than in streams draining upland watersheds.

The estimated carbon accumulation falls near the lower end of the range for the estimate of carbon release from drainage of Histosols and Gleysols, 0.03 to $0.37 \times 10^9 \text{ t yr}^{-1}$ (Table 11). Thus, natural rates of accumulation could be offsetting the release of carbon from disturbance of organic soils and maintaining a small sink, although this appears unlikely. Abandonment of drained lands would also accumulate carbon, but its significance is unknown. In developed countries of Europe and North America, some organic deposits drained in the early 20th century may soon be abandoned and then revert to organic matter accumulation, but new drainage schemes are also underway. Peat accretion in the tropics and the far North may be more significant than in the settled regions, if Neishstadt's paludification projections hold for the circumboreal forests and the tundra, and if rates of accumulation in the tropics exceed those in the temperate zone. Much more data on peat formation is needed, however, before sequestering of carbon in these organic soils can be reliably estimated. The principal weakness in our understanding of wetland carbon dynamics is in the area of decomposition and organic matter transformations within the sediments (Gallagher 1978). There are many data on primary production from a wide variety of wetland types, but carbon degradation rates have not been classified for different wetland types and geographic areas.

MANAGEMENT OF PEATLANDS*

Wetlands, including peatlands and other ecosystems characterized by organic soils, have become recognized for many values, such as absorption of waste nutrients and controlling water supplies (Good *et al.* 1978, Aandahl *et al.* 1974), largely derived from the organic nature of their sediments and their high rates of productivity. Little reference has been made to the potential for wetlands to serve as long-term repositories for fixed carbon, although undisturbed wetlands already carry out this function. Management of wetlands centers on the more recognized values, but, if successful, also assures the functioning of wetlands as carbon sinks. The following discussion describes the major components and challenges in the management of wetlands, as they affect their function as carbon sinks.

Assessing future options for peatlands use depends on first procuring data on classification, mapping and land use. With such a data base, supplemented or updated with remote sensing data, options for decisionmakers can then be outlined. These options must be sensitive to the social, economic and political realities of the countries and regions concerned, but an international overview can encourage governments and the private sector to

*Based on an analysis and presentation by R. S. Dorney.

Table 11. Estimates of carbon release between organic soils and the atmosphere presented in the TIE workshop. Both carbon release (+) and carbon uptake (-) are shown along with assumptions used in each calculation. The uncertainties for the assumptions and estimates are not given. They may range up to an order of magnitude.

A. Estimates of Carbon Release from Histosols (10^9 t C yr $^{-1}$)	Assumptions				
	Carbon Exchange per Area (t ha $^{-1}$ yr $^{-1}$)	Area Drained (10^6 ha)	Bulk Density (g cm 3)	Soil Subsidence from Oxidation (cm)	Carbon Content of Soil (%)
1. (+) 0.05-0.35 (maximum)	+10	5-35			
2. (+) 0.02-0.07		3	0.15	1-3	50%
3. (+) 0.1		2	0.2	5	50%
Range = (+) 0.02-0.35					
<hr/>					
B. Estimates of Carbon Release from Gleysols (10^9 t C yr $^{-1}$)					
1. (+) 0.015	+ 5	3			
2. (+) 0.01	+10	1			
Range = (+) 0.01-0.015					
<hr/>					
C. Estimate of Carbon Sequestration in Peat (10^9 t C yr $^{-1}$)					
1. (-) 0.045	(-) 0.1	450			
<hr/>					
D. Estimate of Net Carbon Exchange (A+B-C) 10^9 t C yr $^{-1}$					
(+) 0.320 to (-) 0.015					

favor some uses over others, and through research and international funding efforts, develop more rational approaches on a long-term basis.

With this strategy, the following options can be suggested:

Creation of Peatlands

With new pressures to improve surface water quality in the United States and Canada (as exemplified by work of the International Joint Commission), and in Western Europe, hydrologically active or sensitive areas will probably be taken out of active crop production to be reforested or allowed to develop natural graminoid plant cover. For example, estimates of the amount of agricultural land surface in southern Ontario which will be committed could be as high as 7% to 10% of the urban surface. Similar areas might be so committed in central and eastern United States as well as in prairie wheatlands in the United States and Canada. At present, the International Joint Commission is proposing such radical land use changes in the Great Lakes basins.

Some of these lands presently in crop production were at one time organic soils (Gleysols or Histosols). Where a conversion in wetland use is made, a gradual return to natural plant cover and its associated geochemical processes would lead to organic carbon accumulation. If alternative economic uses of these wetlands, such as for forestry, fisheries, wildlife or recreation, can be developed, removal of these lands from agriculture will be accelerated. Legislation to protect wetlands, to regulate land use on the floodplain, and to designate natural areas for protection can also add impetus to this potentially substantial wetland creation process.

Functional Designation for Wetlands Management

Functional designation of wetlands identifies natural biophysical processes which benefit man and creates the impetus for maintaining wetlands in a natural state, thereby preserving their carbon storage capacity. For example, some wetlands areas reduce peak water flow, retard snow melting or act as recharge areas, depending on their location in the drainage area, their size and basin ecology. Other wetlands act as nutrient sinks, binding heavy metals and other chemicals in the organic soils and/or the vegetation. Copper, for example, is tightly bound in organic soils. When used for cleansing of waste waters, peatlands can improve water quality. Many wetlands are best preserved for fish and game production and for outdoor education and recreation. If ecosystem evaluation and land-use mapping procedures designate these wetlands functions, a case for retention in a natural state can often be made in design of urban areas, rights-of-way designation, and conversion by drainage or flooding.

Use of Wetlands for Agriculture and Energy Supply

Present uses of peatlands for agricultural production result in large carbon releases. However, growing grasses for animal forage or reclaimed

peatland, a policy adopted in Poland, can reduce or retard subsidence and carbon loss. New or existing food crops, such as wild rice or cranberries, can also conserve the peat soil itself. Thus, carbon storage is not precluded by all forms of agricultural development. If new experimental biomass crops such as cattails, Phragmites, willow, hybrid poplars, and alder are grown on organic soils, conservation of the soil resource may also result.

Synthetic gas production is a new use presently under study by the Institute of Gas Technology in the United States, while in Western Europe and Russia, direct burning for energy is widely practiced. Both these uses irreversibly deplete the peat resource, but flooding can lead to new peat accumulation.

Forestry uses of wetlands (sawtimber, fuel wood, fence posts, mine timbers, Christmas trees, cedar boughs for floral decorations) can be significant local resources managed by small operators or farmers or part of larger commercial logging enterprises. Generally, resource extraction is carried out on a sustained yield basis using either natural regeneration or reforestation to sustain production. Some wetlands exhibit forest regeneration problems, converting more or less permanently to non-commercial trees, shrubs, graminoid plant communities (e.g., cattails) or mosses. In mid-latitudes (e.g., 44° N), breakdown of the top 30 to 60 cm of peat can occur following logging, due to opening of the stands, introduction of more alkaline water (e.g., agricultural liming next to a bog), highway construction across a bog on calcareous till, or blocked drainage from logging roads. Forestry activities, however, generally do not damage the total peat resource and are compatible with long-term maintenance of carbon storage capacity, in addition to providing a renewable energy source.

Preservation as an Option

Some peatlands should be preserved intact as natural reserves or as ecological research areas. Designation should be based on the present state of naturalness and freedom from surrounding effects or impacts, size, and performance of valued ecological and public service function. Preservation ensures the continued function of wetlands as carbon sinks, and preserves options for future management.

DATA UNCERTAINTIES AND RESEARCH NEEDS

Uncertainties in Available Data

Review of available data on the organic soils of the world suggests that human intervention may have converted these natural carbon sinks into carbon sources. Data uncertainties are substantial, however, and this conclusion could be wrong. Organic soils may now be in balance with respect to carbon exchange, or they may still be operating as a sink, though at a lower level than during presettlement times. Workshop participants identified the principal deficiencies in existing data that must be corrected in order to resolve the issue of the significance of organic soils to the world

carbon budget.

Estimates of the Global Extent of Gleysols and Histosols

- Uncertainty connected with present estimates of world deposits of organic soils (Gleysols and Histosols) may be as low as 20%, if figures derived from FAO summaries are reliable. Considering uncertainties associated with data for the USSR, China, and certain tropical deposits, the precision is likely to be $\pm 50\%$ of the estimate given by Bohn (1976), which is 4.3×10^8 ha for the world. For certain little-known areas, there are no accurate estimates of the extent of organic soils deposits, and present figures, though offered as the best available, are only assumptions.

Rates of Oxidation of Soil Carbon as a Result of Human Intervention

- Current estimates of carbon oxidation rates are based on measured values for relatively few sites, such as the Sacramento-San Joaquin Delta and southern Florida. Data are insufficient to determine whether figures for those sites are typical, and the extent of uncertainty for estimates of regional or continental deposits may be as high as 50% to 100%.

For many parts of the world, but particularly for tropical eastern Asia, China, and the USSR, little information exists on the extent of drainage and expected oxidation of organic deposits in the recent past, the present or the near future. As a result, the present level of precision can be no less than 100% for estimates of changes in world pools of organic soils.

Importance of Paludification in Northern Peatlands

- The apparent rapid expansion of peatlands in western Siberia and the lack of comparable information for Canada and Alaska leave an insufficient data base for appraising the importance of paludification in the net withdrawal of carbon from the atmosphere. Verification of current rates of expansion of peatlands is needed for all deposits, particularly those of the boreal and sub-boreal zones. Information is lacking about the long-term lateral spread of peatlands as well as the rate of carbon absorption during this process.

Extent of Tropical Peatlands

- Recent estimates of the extent of organic soil deposits in tropical countries have been widely cited (e.g., Moore and Bellamy 1975), but they are underestimates. New assessments, presented in this workshop, suggest that the peatlands of southeast Asia, Indonesia, and North and South America are larger than previous estimates allowed. However, the rate of drainage and development of these peatlands is completely unknown. Although the importance

of soil temperature in governing rates of oxidation of soil carbon is recognized, its significance in relation to the tropics must be investigated.

Carbon Release from Past Agricultural Development of Wetland Soils

- Carbon release resulting from the opening of moist prairie and marsh soils in the temperate zone during the 19th and early 20th centuries has been variously estimated. Even if the release of 110×10^9 t C suggested by Wilson (1978) is only approximately correct, carbon loss during this period may be significant in relation to the atmospheric CO₂ concentration. There has been no summarization of available data on the consequences of these historical events. Similarly, though extensive drained areas have been abandoned since the period of major interventions into organic soils, their significance in creating a carbon sink has not been estimated.

Effects of Fossil Fuel Combustion Products on Wetland Processes

- Little is known about the influence of fossil fuel combustion by-products, such as nitrogen and sulfur, on wetland processes and natural rates of growth or degradation of peatlands. Destructive effects of acid rain and other pollutants on wetland processes are also unknown, but they may be regionally significant.

Although increased atmospheric carbon dioxide could stimulate the photosynthetic rate of wetland plants, it may not have a significant effect on wetlands, because photosynthetic rate is not the principal limiting factor regulating wetland growth. However, increasing CO₂ may increase global temperatures, which could have a significant effect on the growth rates of peatlands. A warming climate in the higher latitudes could have an important impact on rate of accretion of peatlands, paludification, and release of carbon due to withdrawal of permafrost from tundra bogs. At present, data are insufficient for even an approximate estimate of the dynamics of the processes under the influence of changing climate. The response of wetlands to recent changes in climate is not well known. Radioisotope dating, which provides averages over some millenia, does not give any precise estimates for the period since the 19th century.

Changing Interpretation of Resource Values and the Wetland Carbon Pool

- Until now, development of organic soils for fuel and other products has probably not occurred to an extent that is significant in terms of global carbon exchange, but energy shortages are stimulating an increased interest in utilization of peat for fuel. There is also continued drainage of peatlands for afforestation. The cumulative effects of human interventions are not sufficiently known to permit an estimate of the impact of present and future human

activities on the function of peatlands as carbon reservoirs.

Research Recommendations

Evidence established at the workshop shows that human activity has converted organic soils from a net carbon sink into a carbon source for at least part of the time since major interventions into these soils began. Data suggest that organic soils may now be releasing an amount of carbon within the range of 1.3% to 16.1% of the net increment of carbon added annually to the atmosphere. In the late 19th and early 20th centuries, the amount of carbon release from organic soils may have been even greater.

There is, however, a need for better information about the significance of organic soils today. Because estimates for net carbon exchange are too uncertain to permit definitive conclusions, workshop participants recommended research initiatives to resolve data uncertainties over the next several years, by meeting the following goals:

1. improvement of estimates of the global extent of organic soils
2. identification of areas subject to drainage
3. estimation of peat accretion rates in northern boglands
4. determination of the extent of peatlands and other organic soil deposits in presettlement areas of North America and Europe
5. evaluation of the effects of pollutants upon production, decomposition, and peat accretion in wetlands
6. evaluation of the behavior of wetlands under the influence of changing climate
7. assessment of the significance of energy resource development for peatland carbon exchange
8. establishment or designation of an organization to coordinate field research and synthesis activities by researchers in many countries.

Improving Estimates of the Global Extent of Organic Soils

- In order to reduce uncertainties in critical areas and to test the validity of existing mapping and ecosystem-based estimates of pool sizes, critical areas for which further data are most needed, principally in the tropics and the far North, should be identified.
- A well-defined field measurements program, coupled with remote sensing and vegetation analysis, should be initiated at carefully chosen sites. The Florida Everglades, Minnesota peatlands, or other well-studied sites should be used for ground truth and methods calibration. Soil depth and bulk density should be determined at all measurement sites.

Identifying Areas Subject to Drainage

- Sites that are undergoing drainage or will be subject to drainage

in the near future should be located. Data may be obtained from agencies such as the United Nations, International Council of Scientific Unions, or International Peat Society, from foreign scientists, and from agriculture and forestry agencies in countries with major organic soils pools.

- In areas where major interventions are likely, soil samples from different depths should be analyzed for carbon content and bulk density, and permanent benchmarks should be established so that subsidence rates can be monitored.
- Since a coordinated, multi-national effort will be required to monitor drainage of organic soils, foreign and U.S. scientists and international agency officials should meet to compile information on peatland development programs and to plan a program of field measurements.
- Remote sensing should be explored as a means of estimating areal changes that result from the spread of agriculture or urbanization of wetlands. Use of outgoing thermal radiation (nocturnal cooling patterns) to distinguish drained from undrained Histosols has yielded promising results. Microwave sensing, in conjunction with remote sensed surface temperature analysis, may improve resolution and should be further tested.

Estimating Peat Accretion Rates in Northern Boglands

- In North America: Investigation should be started in Canada and Alaska to corroborate reports of rapid paludification in Siberia. A study should be made of release of peat from permafrost in response to global temperature amelioration, to determine whether the process is an important source of carbon. Parallel measurements of peat accretion and peat oxidation should be made at representative sites.
- In the Soviet Union: Because little is known about extensive peat beds in Siberia, Soviet and Scandinavian ecologists and peat scientists should be sought to cooperate in the effort to identify sites for study and to gain data about peat accretion in their countries.
- In the temperate zone: To improve carbon exchange estimates for the more settled parts of the temperate zone, permanent benchmarks should be established, and low-intensity, long-term monitoring programs for such key variables as bulk density and soil carbon and nitrogen content should be initiated. Data on oxidation and subsidence rates are available for a few sites, such as Holland Marsh in Ontario and the Florida Everglades, but a wider range of estimates is needed to determine whether available data are representative. With bulk density and subsidence rate data, peatland oxidation rates can be estimated, based on the established

relationship between subsidence rate and carbon loss.

Determining the Extent of Peatlands and Other Organic Soil Deposits in Presettlement Areas of North America and Europe

- A historical assessment should be made as a partial check on the results of carbon isotope work, which suggests that large quantities of carbon were released to the atmosphere by the opening during the past century of mid-continental rich grassland soils. With presettlement and bulk density data from current desposits, an estimate could be made of total carbon losses from draining, ditching, and vegetation clearing. The new historical data would be a valuable source of information to ascertain the magnitude of the impact of a single sustained human activity on a global elemental budget.

Evaluating the Effects of Pollutants upon Production, Decomposition, and Peat Accretion in Wetlands

- Research efforts should be made to improve understanding of the limiting factors that control production, decomposition, and peat accretion in wetlands. The influence of sulfur, nitrogen, heavy metals, and other elements may have considerable bearing on the source-sink relationships of organic soil deposits.

Evaluating the Behavior of Wetlands under the Influence of Changing Climate

- Since little is known about what might happen to wetlands carbon dynamics if average temperatures rise as a result of carbon dioxide enrichment, long-term behavior of peatlands in response to natural climatic change should be summarized and interpreted. The best approach may be to compile available data and then do mathematical modeling. If the basis for modeling is not strong enough, however, more empirical data should be gathered before model building and model validation are begun.

Assessing the Significance of Energy Resource Development for Peatland Carbon Exchange

- A study should be made of the implications for the world carbon cycle of the large-scale utilization of peat that may result from the current search for reliable energy resources. Local ecological effects, such as change in the water table, may be even more significant than carbon cycle effects, if a large amount of peat is harvested for fuel. Since massive peat deposits occur in areas not convenient to central power generation, increased peat utilization is likely, particularly in the USSR, Scandinavia, Ireland, and North America. The study should examine whether harvesting permanently alters the capacity of a site to function as a carbon sink or source of other benefits. The study will probably require additional field data to further understanding of effects

of large-scale peat removal from specific ecosystems.

Establishing an Organization to Coordinate Field Research and Synthesis Activities by Researchers in Many Countries

- Because many of the recommended research initiatives require coordination of geographically dispersed field research and synthesis activities, an organization should be established or designated to maintain liaison with foreign scientists and agencies, to integrate research, modeling, and compilation activities, and to assure overall program coordination.

WORKSHOP CONCLUSIONS

Despite major gaps in available data on the world's organic soil deposits, evidence suggests that carbon fluxes may be large enough to be significant in the world carbon budget. Both carbon sequestering and liberation of organic carbon are occurring simultaneously in different locations at different rates. Although wetlands are natural sinks for atmospheric carbon, carbon release from human disturbance of wetlands is the dominant process of consequence. The following are the major findings of the workshop:

- The present annual carbon release has been estimated to vary from 0.03 to 0.37×10^9 t from world Histosols and Gleysols. The upper limit is based on the assumption that maximum utilization of Histosols occurs. While this range is about 1.3% to 16% of annual rise in atmospheric carbon, probably not all the released carbon remains airborne. If half of the released carbon remains in the atmosphere, organic soils contribute 0.6% to 8.0% of the annual rise in atmospheric carbon dioxide. Uncertainties imply that an even larger contribution is possible.
- Present releases of carbon from the Everglades Agricultural Area and the Sacramento-San Joaquin Valley in California together -- about 0.17×10^9 t per year -- suggest that the lower limit of the world estimate is too low, particularly if major drainage of organic soils is occurring in the tropics. Knowledge of the areal extent of tropical deposits, for which estimates vary widely, and of present and planned drainage schemes must be increased before the carbon budget implications of soil reclamation can be analyzed.
- Clearing and draining of organic soils in the temperate zone during the late 19th and early 20th centuries may have released more carbon annually at that time than in recent decades. Although estimates of carbon release in excess of 100×10^9 t have been suggested, the actual value may be a smaller but still significant quantity. Data are too sparse to resolve this question but could be forthcoming from historical analysis of the pattern of organic soil

drainage in the developed areas of North America and Europe.

- The present annual rate of carbon sequestering in organic soils is estimated at 0.045×10^9 t per year. Since this estimate is near the lower limit of the estimated range for carbon release, the net exchange of carbon from organic soils could balance out to zero, although wetlands are more likely to be net carbon sources. The estimate of carbon sequestering is based on only a few studies and should be improved.
- Better estimates of atmospheric exchange of world organic soils can be made if existing data are collated, especially in collaboration with foreign scientists. Data acquisition will be needed for principal carbon pools in the tropics, USSR, China, and, to a lesser extent, North America.
- Identifying major drainage programs is a top priority that must precede careful selection of sites at which benchmark soil measurements can be made periodically. A relatively small number of core measurements in critical areas is sufficient, if they are coupled with greater awareness of wetland development plans. Results from these measurements would significantly improve our understanding of wetland carbon exchange within two to four years after program initiation.

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WORKSHOP PARTICIPANTS

CO₂ Workshop on Organic Soils

May 7 and 8, 1979

Dr. Leon H. Allen, Jr.
Soil and Water Unit
University of Florida
Gainesville, FL 32611

Dr. C. C. Delwiche
Department of Soils
University of California-Davis
Davis, CA 95616

Dr. C. J. Richardson
School of Forestry and
Environmental Studies
Duke University
Durham, NC 27706

Dr. Robert S. Dorney
Vice President
Research and Development
Ecoplans, Ltd.
Waterloo, Ontario
Canada N2L 4E2

Dr. John Duxbury
Agronomy Department
Cornell University
Ithaca, NY 14850

Dr. Hinrich L. Bohn
Department of Soils, Water and
Engineering
University of Arizona
Tucson, AZ 85721

Dr. S. P. Mathur
Chemistry and Biology Research Institute
Agriculture Canada
Ottawa, Ontario
Canada K1A 0C6

Dr. D. E. Willard
School of Public and Environmental
Affairs
Indiana University
Bloomington, IN 47405

Dr. Rouse Farnham
Department of Soil Science
University of Minnesota
St. Paul, MN 55108

Dr. Donald Franzmeier
Department of Agronomy
Purdue University
Lafayette, IN 47907

Dr. Orie L. Loucks
Science Director
The Institute of Ecology
Holcomb Research Bldg., Butler University
Indianapolis, IN 46208

Dr. Thomas V. Armentano
Research Scientist
The Institute of Ecology
Holcomb Research Bldg., Butler University
Indianapolis, IN 46208