

The potential storage of carbon caused by eutrophication of the biosphere

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ABSTRACT

We use an element-matching approach to examine the hypothesis that the rate of atmospheric CO₂ increase has been reduced by an increased net storage of carbon in forests, coastal oceans, and the open sea caused by eutrophication of the biosphere with nitrogen and phosphorus. We conclude that a reasonable upper limit of about 200 Tg of the estimated total of 7800 Tg of CO₂-carbon released to the atmosphere in 1980 could have been stored in biotic reservoirs as organic carbon in trees, soils, and aquatic sediments as a consequence of eutrophication. The reason that storage is so limited relative to total carbon release is that the C:N and C:P ratios in the CO₂-carbon sources (fossil fuels and primary forests) are much larger than the ratios in the sinks (regrowing forests and aquatic sediments) and that N and P supply controls the rate and amount of storage of organic carbon in the available biotic sinks.

1. Introduction

Dramatic changes in the carbon cycle over recent decades have been paralleled by equally large changes in some segments of the cycles of nitrogen, phosphorus and sulfur (Delwiche and Likens, 1977). These cycles are linked through biological processes because these elements together with hydrogen and oxygen are also the major elements in the biota of the earth. Redfield (1958) and Redfield et al. (1963) have noted that the "interactions of organisms and environment are reciprocal" and "the influence of organisms on the composition of their environment is determined by physiological influences and consequently exhibits the regularity inherent in organic processes." Lovelock (1979) has taken these considerations even further to suggest that the composition of the atmosphere-ocean system is controlled by organisms in a homeostatic manner to maintain environmental conditions within the range favourable to life processes. The theses of Redfield and Lovelock have great appeal for biologists because we see so many of the life processes we study in terrestrial and aquatic ecosystems reflected in changes in the

chemical composition of the water and air flowing through these systems. We know that biotic processes do affect the chemistry of air and water.

The general purpose of this paper is to outline a framework for considering the biota-mediated linkages in the global cycles of C, N, and P. The specific purpose is to examine the hypothesis that the rate of atmospheric CO₂ rise has been reduced by an increased net storage of carbon in forests, coastal oceans, and the open sea caused by the man-induced acceleration of the nitrogen and phosphorus cycles. In the calculations, we have attempted to provide a reasonable upper limit to the storage of carbon. It is certainly possible to calculate larger storages, but these larger storages are inconsistent with our understanding of the biogeochemistry of forests, rivers and oceans.

2. Dimensions of the problem

The atmospheric CO₂ concentration has been increasing in the period from 1958 to the present (Bacastow and Keeling, 1981). While it is clear that one source of this increase is fossil fuel burning

(Rotty, 1981), there is also a second large net CO₂ source from forest harvest and clearing (Houghton et al., 1983). In 1980, the CO₂ source from fossil fuel was about 5.2×10^{15} g C yr⁻¹ (Rotty 1981) and the source from forest clearing was about 2.6×10^{15} g C yr⁻¹ (Houghton et al., 1983) for a total release of 7.8×10^{15} g C yr⁻¹. The major CO₂ sources and sinks are identified in eq. (1).

$$\begin{aligned} & \text{Sources} \\ & \text{fossil fuel} + \text{harvest and clearing} \\ & \text{Sinks} \\ & = \text{atmospheric increase} + \text{ocean uptake} + \text{residual by difference} \end{aligned} \quad (1)$$

Attempts to solve this equation have frequently led to an excess of carbon released by the CO₂ sources relative to the increased CO₂ content of the atmosphere and ocean pools (Broecker et al., 1979). The residual carbon sinks have not been identified. Errors in the estimates of the source and sink terms may account for a portion of the excess. It is also possible that other sinks may be involved. Regardless of the size or sign of the residual term, it

is important to determine whether biotic mechanisms can be important in limiting the atmospheric CO₂ increase. In this paper, we examine three sinks for organic carbon that seem potentially important: forests and their soils, continental shelf sediments, and the deep portion of the oceanic water column plus the sediments of the open ocean.

3. Element ratios in the sources and sinks of carbon

Table 1 summarizes much of the data needed to test the idea that increased carbon storage in forests and oceans is occurring as a result of eutrophication. Several points from the table should be noted. (i) The total of terrestrial net primary production (NPP) and aquatic NPP is still large relative to the recent rate of fossil fuel CO₂ release and thus the capacity for biotic activity to alter the atmospheric CO₂ balance exists. (ii) The combustion of fossil fuels releases about half as much nitrate (20 Tg N yr⁻¹) into the atmosphere as the nitrogen fertilizer industry produces in a year. (iii) The C:P and the C:N ratios in fossil fuel and to a

Table 1. Selected annual fluxes and elemental ratios in the global circulation of carbon and nutrients (for 1980).

Category	Source	Flux (Tg yr ⁻¹)	Elemental ratios by weight	
			C : N : P	C : N
1. Terrestrial NPP	(Whittaker and Likens, 1975)	55,000 C		
Vegetation	(Likens et al., 1981)		800 : 9 : 1	90
Litter	(Likens et al., 1981)		500 : 10 : 1	50
Soils	(Likens et al., 1981)		120 : 10 : 1	12
Forests only	(Whittaker and Likens, 1975)	40,000 C		
Vegetation	(Melillo and Gosz, 1982)		1500 : 10 : 1	150
Litter	(Melillo and Gosz, 1982)		500 : 10 : 1	50
Soils	(Melillo and Gosz, 1982)		120 : 9 : 1	13
2. Aquatic NPP	(Platt and Subba Rao, 1975)	30,000 C		
Plankton	(Redfield, 1958)		40 : 7 : 1	6
Sediments	(Froelich et al., 1982; Rosenfeld, 1981)		80 : 7 : 1	12
3. Fossil fuel*	(Rotty, 1981; Delwiche and Likens, 1977)	5,200 C	9000 : 36 : 1	250
4. Nitrogen fertilizer production	(United Nations, 1978)	50 N		
5. Phosphate fertilizer production	(United Nations, 1978)	12 P		

The units are Tg per year (Tg = 10¹² g).

*The oxidized nitrogen released via fossil fuel combustion includes that generated from atmospheric N₂ in the combustion process.

lesser extent in forest biomass are very high relative to the ratios in the terrestrial soils, plankton, and marine sediment pools. We also know that productivity of both forests (Miller and Miller, 1976) and aquatic ecosystems (Ryther and Dunstan, 1971) can be stimulated by added nutrients; however, the stimulation of production by added CO₂ alone is questionable for forests (Kramer, 1981) and probably out of the question for most fresh water aquatic ecosystems and oceans (Schindler, 1971; Broecker, 1974). In this paper, we assume that added nutrients are required to stimulate additional carbon storage in any of the biotic reservoirs.

The conceptual model of the carbon flows to be considered here is illustrated in Fig. 1. We emphasize the exchanges of carbon between the organic reservoirs and the atmosphere. Conceptually, the atmosphere includes the total dissolved CO₂ in the surface oceans because this freely exchanges with atmospheric CO₂. We assume that there was a period before the industrial revolution during which the total of the net primary production of the biotic compartments, terrestrial ecosystems, rivers, the coastal ocean and the open ocean, was balanced by their net ecosystem

respiration. We assume that in the pre-industrial steady state, the total organic carbon in the biosphere was constant; even the small storages of carbon that occurred as sedimentary rock was formed from coastal and oceanic sediments was balanced by an equal release of this carbon from weathering in the terrestrial ecosystem. Thus with respect to the atmosphere-biosphere exchanges, $A = B$, or the sum of $a_1, a_2, a_3 \dots$ equals the sum of $b_1, b_2, b_3 \dots$ in Fig. 1.

The individual compartments of the biosphere need not be in carbon balance with the atmosphere for the total biospheric CO₂ uptake to equal total biospheric CO₂ release. Organic carbon has always flowed from forest to the ocean via rivers where much of this carbon is oxidized to CO₂. Even an increase in the export of organic carbon from the land to the rivers and the coastal ocean does not necessarily indicate a change in the net CO₂ flux between the atmosphere and the biosphere. It may simply indicate a redistribution of organic carbon which erodes from the land surfaces and is deposited in riverine and coastal ocean sediments. For a change in the atmospheric-biospheric carbon balance to occur, the change in location of the

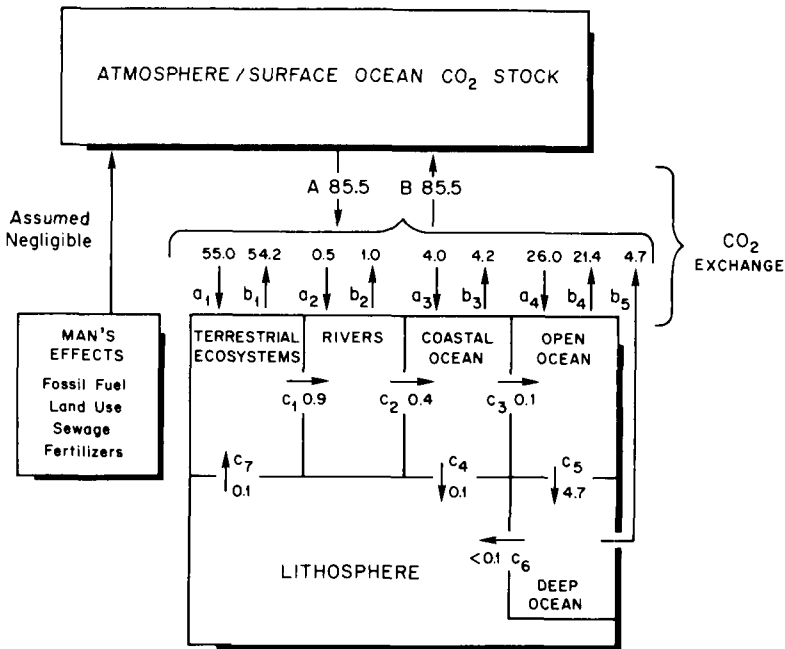


Fig. 1. The steady-state fluxes of the pre-industrial global carbon cycle (10¹⁵ g C yr⁻¹).

carbon must be accompanied by a change in the fraction of this organic carbon respired.

4. Potential carbon storage in forests, rivers, coastal oceans and the open seas

We will now examine the response of the biotic reservoirs of carbon to the perturbations induced by human activities including fossil fuel use, changes in land use, sewage disposal and dispersal of nitrogen and phosphorus fertilizers. We seek to answer the following question: "How much could these perturbations have changed the distribution of carbon between the atmosphere and the biosphere?"

4.1. Forests

The forests and forest soils of the earth contain more than 90% of the biosphere's carbon and in recent times they may have been fertilized by increasing nitrogen in precipitation (Deevey, 1970). These increases in nitrogen content of precipitation are related to fossil fuel combustion (Table 1).

We have calculated a reasonable potential increase in carbon storage in forested ecosystems due to this eutrophication (Table 2). The forests have been divided by region and by the compart-

ments of vegetation, litter, and soil since both the stature of the forests and distribution of carbon by compartments are different in different regions. We have assumed that 6 Tg N yr⁻¹ or about 30% of the fixed nitrogen released in fossil fuel combustion actually reaches forests via atmospheric transport and precipitation. We have assigned 4 Tg to temperate forests, 1 Tg to boreal forests, 0.5 Tg to tropical forests, and 0.5 Tg to woodlands and shrublands, reflecting the non-uniform distribution of fossil fuel use (Melillo and Gosz, 1982) and the regional pattern of nitrate deposition. We further assume that the forests retain only 60% of the added nitrogen and that this is invested in net growth of the vegetation, litter, and soil compartments in proportion to the initial nitrogen distribution in these compartments such that the C:N ratios of the compartments do not change. The results of the calculations demonstrate that if storage is occurring, most is in temperate forest vegetation and soils because the temperate zone receives most of the nitrogen inputs. The total potential storage is a large amount, about 100 Tg C yr⁻¹. However, since this is an annual increment of only one part in about 5000 of the total forest carbon, even in the most heavily fertilized temperate region, detecting such a change by empirical measurement of forest carbon stocks would be

Table 2. Potential carbon storage in forests due to nitrogen loading from fossil fuel (modified from Melillo and Gosz, 1982)

Region	Area (10 ⁸ ha)	Carbon mass (kg C m ⁻²)	Compartments (% of N)	N load (Tg yr ⁻¹)	C storage (Tg yr ⁻¹)
Tropics	24.5	31.5	vegetation (14.8)	0.5	6.7
			litter (0.3)		0.1
			soil (84.8)		3.3
Temperate	12	29.1	vegetation (10.3)	4.0	37.1
			litter (2.3)		2.8
			soil (87.4)		27.3
Boreal	12	26.5	vegetation (5.4)	1.0	4.9
			litter (3.2)		1.0
			soil (91.5)		7.1
Woodland and shrubland	8.5	13.2	vegetation (6.9)	0.5	3.2
			litter (1.0)		0.2
			soil (92.0)		3.6
Totals				6.0	97.0

quite impossible in the short term. Empirical studies of forest growth have shown both positive and negative growth trends in industrialized countries in recent decades (Whittaker et al., 1974).

Our calculations indicate the maximum reasonable carbon accumulation due to eutrophication. There are several reasons why this potential may not have been realized: (1) some of the increment in the atmospheric nitrogen load may be lost through denitrification and thus can not be used in biotic processes that result in carbon storage; (2) some forests are probably not nitrogen limited and thus would not store carbon if nitrogen loading were increased; (3) as ecosystems become richer in this nutrient, added nitrogen may be used with less efficiency and hence cause less carbon storage; (4) increases of nitrogen in precipitation are accompanied by increases in hydrogen ion, sulfate, heavy metals and other toxins which may limit the ability of the forest to respond to nitrogen fertilizer. Forest responses are treated in greater detail by Melillo and Gosz (1982).

We have not considered grasslands, tundra, and deserts because of their limited ability to store large amounts of carbon in response to the current levels of nitrogen eutrophication. This is because they lack the large woody compartment with its high C:N ratio which permits a large amount of carbon storage per unit nitrogen input in forests.

4.2. Rivers

The role of rivers in the global carbon cycle has been considered in detail in a recent DOE Report (U.S. Dept. of Energy, 1981). In the preindustrial steady-state carbon flow in rivers, inputs of organic carbon exceeded the outputs (Fig. 1). Net primary production in rivers was about 500 Tg C yr⁻¹ and allochthonous input from terrestrial ecosystems was 900 Tg C yr⁻¹. Respiration returned 1000 Tg C yr⁻¹ to the CO₂ pool and export of organic carbon to the coastal ocean was 400 Tg C yr⁻¹. Human activity has resulted in erosion of soil carbon into rivers. It is not established whether or not this erosion process has changed the atmosphere-biosphere carbon balance, because we do not know whether the degree or rate of oxidation of this carbon has been changed by this transfer. We conclude that there has been no significant increase in carbon storage in rivers but we address the impacts of changes in carbon and

nutrient transport via rivers to the coastal ocean next.

4.3. The coastal zone

Human activity is concentrated in the coastal zone and wastes from this activity have an impact on coastal oceanic production and possibly on carbon storage. In addition to fertilizers lost from agricultural lands, sewage, and combustion products from fossil fuel burning, there is the possibility that the extensive oxidation of natural organic matter from forest clearing and harvest and from soils under agriculture will generate additional flows of nitrogen and phosphorus in waters draining the continents. For example, in 1980 the net oxidation of 2600 Tg C from forest clearing and agricultural conversions (Houghton et al., 1983) would presumably mobilize about 70 Tg N and 9 Tg P, amounts which rival global fertilizer production for both N and P (Table 1). However, the amounts of nutrients reaching the coastal oceans must not be overestimated by double accounting. For example, nutrients in sewage may originally come largely from fertilizer production and nitrogen in rivers may be derived partly from fossil fuel nitrogen pollution from the atmosphere.

We have used Meybeck's recent comprehensive summary of the fluxes of C, N, and P to the coastal ocean based on measurements from a large sample of rivers in both heavily polluted and more pristine areas (Meybeck, 1982; Table 3). Increased carbon storage in the coastal zone sediments could be occurring through two mechanisms: (1) the burial of excess (above the preindustrial steady-state) organic carbon carried by rivers to the oceans and (2) the burial of some fraction of the increased primary production due to eutrophication (Fig. 2). Because of the lack of information on change in organic carbon load in rivers, Meybeck chose not to present a number for man-derived C. We estimate 100 Tg C yr⁻¹ for illustrative purposes as this seems to be a plausible amount based on the uncertainty of Meybeck's numbers for annual total organic carbon transport (400 Tg C yr⁻¹ ± 30%) and Meybeck's more thoroughly documented increases in N and P. Therefore, the potential maximum *increment* to burial from carbon export via rivers to the coastal ocean is 100 Tg C yr⁻¹. It is a maximum potential because some of this 100 Tg C may be either oxidized in the coastal ocean or

Table 3. *Global fluxes to the ocean of carbon, nitrogen and phosphorus in rivers (adapted from Meybeck, 1982)**

Category	Natural flux (Tg yr ⁻¹)	Man derived (Tg yr ⁻¹)
Carbon		
dissolved organic carbon	215	
particulate organic carbon	180	100.0†
total	395	
Nutrients		
nitrogen		
nitrate	3.75	
ammonium	0.50	
dissolved organic	11.00	7.0 TDN‡
particulate organic	21.00	
total	36.25	
phosphorus		
phosphate	0.45	
dissolved organic	0.55	1.0 TDP‡
particulate organic	8.00	
particulate inorganic	12.00	
total	21.00	

* Corresponds to drainage of 100×10^6 km² out of total land surface of 149×10^6 km² (omits interior drainages and glaciated areas).

† A rough estimate based on discussion in Meybeck (1982) and on data from highly impacted Asian drainages reported by Milliman and Meade (1983) and by Milliman (personal communication).

‡ TDN refers to total dissolved nitrogen, TDP refers to total dissolved phosphorus.

exported to offshore ocean waters and thus escape burial. In an attempt to refine this crude estimate of increased carbon storage, we have examined information on changes in coastal zone productivity and on coastal zone sedimentation.

Net primary production in the coastal zone has probably been increased by man's N and P loading of coastal waters. The increase in the load of dissolved N to coastal oceans (7.0 Tg N yr⁻¹) is 7 times greater than that of dissolved P (Table 3). Since this is close to the weight ratio of N:P in plankton (Table 1), the question of whether N or P is limiting coastal productivity is avoided as the calculation of potential C storage will be similar in either case. The total net primary production in the coastal zone of about 4000 Tg C yr⁻¹ (Ryther, 1969) is supported, as is most productivity in

aquatic ecosystems, by recycled nutrient. Burial of organic matter requires addition of nutrients from outside the system, such as from rivers, lest the system run down. Therefore, an increase in carbon burial requires increased nutrient loading, and using Meybeck's estimate of man-derived nutrient loading, the potential carbon burial is 40 to 80 Tg C yr⁻¹ from increased plankton production. The upper end of this range allows for the fact that early diagenesis in some sediments regenerates N and P preferentially relative to organic carbon over a period of years. These released nutrients may re-enter the water column and possibly deliver more organic carbon to the sediments. In permanently buried material the C:N and C:P ratios (by weight) may be twice the Redfield ratios of 6:1 and 40:1 respectively (Rosenfeld, 1981; Froelich et al., 1982). Alternatively, the regenerated nitrogen may be lost from the system by denitrification and phosphorus may be lost through chemical precipitation as insoluble mineral and thus the regenerated nutrients may not be available to sequester additional carbon in sediments.

Berner (1982) has shown that in the coastal zone, only a small fraction of the net primary production plus the organic carbon entering from rivers is buried in sediments (Table 4). Most of the carbon burial in the modern ocean occurs in continental shelf and slope sediments. Berner calculates the burial rate by multiplying the global flux of continent-derived sediment, most of which is deposited on the continental shelves, by their mean percent organic carbon content of 0.75% for a burial of 130 Tg C yr⁻¹. This will be reduced by some 20% due largely to decomposition via sulfate reduction in these anoxic sediments to about 100 Tg C yr⁻¹. The recent increment to burial due to increasing human activity must be only a fraction of this; probably an upper limit of 50 Tg C yr⁻¹ could be defended.

A comparison between the maximum amount of carbon potentially available for burial and the amount buried as calculated by Berner reveals two interesting points. The first is that a large fraction of the carbon coming down rivers is most likely metabolized to CO₂, although some may be exported from the shelf as dissolved organic carbon. The second is that only a small fraction of total net primary production of the coastal ocean is buried and of this the man-caused increase is probably 50% or less. Our estimate of the

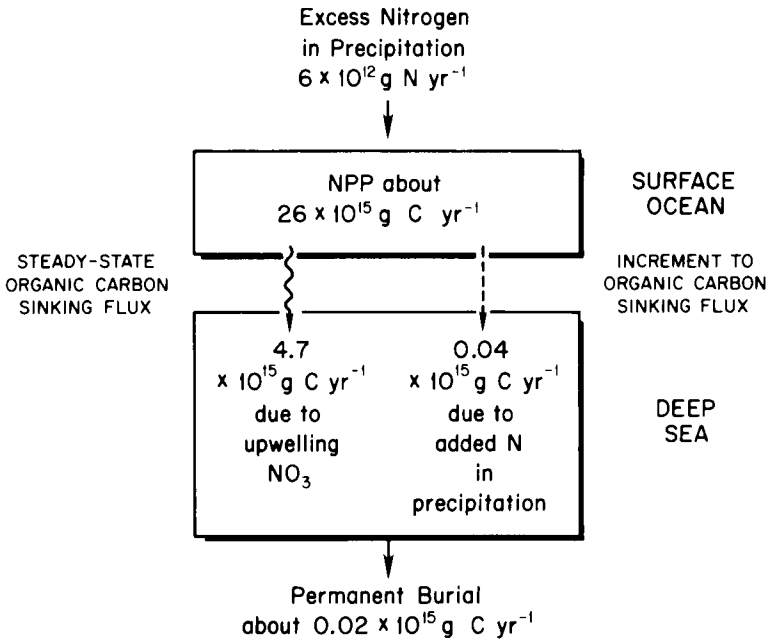


Fig. 3. Estimated increase in organic carbon sedimentation caused by excess nitrogen in precipitation.

“sink” may be only a temporary one. Also, if the total supply of N and P were in balance relative to the needs of the plankton, the rate of P supply would serve to limit this excess nutrient-matching carbon flux. It is interesting to note that the forests have the potential to store, with the same nutrient load, about twice as much carbon as does the plankton system because of the higher C:N ratio of forest ecosystems.

5. Additional mechanisms for storing carbon

Our analysis of potential carbon sinks has not been exhaustive. Several questions remain to be answered.

Is there the possibility that increases in CO_2 alone will stimulate carbon storage, especially in terrestrial ecosystems? If this occurs, it implies either a widening of the C:N ratio in the organic matter pools or an increase in nitrogen fixation or retention in terrestrial ecosystems. However, the impact of man appears to be moving terrestrial systems in the other direction, since early suc-

cessional forests have lower C:N and C:P ratios than mature forests. It is the rapidly disappearing mature forests that contain the most organic carbon per unit nutrient. Thus, by cutting mature forests we are decreasing the carbon storage on land and releasing nutrients to downstream ecosystems which store less carbon per unit of nitrogen and phosphorus than mature forests.

Are there other sinks that may remove excess atmospheric CO_2 not considered here? There are several possibilities.

(a) Mulholland (1981) estimates that carbon accumulation rates in river delta regions may have averaged 600 Tg C yr^{-1} over the last 12,000 years. One important question is whether or not there has been a recent increase. Even if there has been an increase, movement of carbon from uplands to lowlands by erosive processes does not necessarily result in net carbon storage.

(b) The net primary production of marine macrophytes is about $1000 \text{ Tg C yr}^{-1}$ but there is no evidence that global macrophyte biomass or carbon storage due to macrophyte activity has been altered in recent decades. Thus Smith’s (1981) suggestion that marine macrophytes are important in the atmospheric CO_2 balance seems unlikely.

(c) The formation of calciche (carbonates) in soils of arid regions may serve to sequester CO_2 , but the net rate of formation is only about 20 Tg C yr^{-1} globally (Schlesinger, 1982) and thus minor perturbations in this flux would have little impact on atmospheric CO_2 levels.

(d) The net accumulation of carbon in developing soils is probably small (Melillo and Gosz, 1982). For example, we calculate that the accumulation of carbon in tundra and boreal regions that were glaciated about 10,000 years ago has been only 50 Tg C yr^{-1} if a linear increase to the total current stock is assumed.

(e) The idea that the formation of charcoal during forest clearing and burning has sequestered significant amounts of carbon (Seiler and Crutzen, 1980) has been examined by Houghton et al. (1983); charcoal formation reduced the amount of CO_2 released due to forest clearing by only about 3% over the period 1860 to 1980. Seiler and Crutzen's argument leads to a very high portion of the soil organic matter pool being elemental carbon. Houghton et al. (1983) conclude that the charcoal sink is much smaller. Current work is reexamining the question (Post, pers. comm.).

(f) MacKenzie (1981) argues that the increasing CO_2 level in the surface ocean will dissolve shallow water magnesian calcites but that the potential additional ocean CO_2 uptake resulting from this mechanism is only about 1% of the fossil fuel CO_2 release.

(g) During the last two decades, a number of developed countries have attempted to implement a policy of wildfire suppression. This has led some scientists to argue that fire suppression has led to a net accumulation of carbon (e.g., Seiler and Crutzen, 1980). Two lines of evidence can be used

to counter this argument. First, while wildlife suppression can often prevent small fires, it results in the accumulation of large amounts of "fuel" in forests. These large fuel accumulations often give rise to large fires that are difficult to control. Second, on the global scale wildfires may be occurring at a more rapid rate than they did in the past. In remote sectors of the tropical countries, the fires used to clear land for agriculture are escaping and burning large tracts of previously seldom burned areas.

6. Summary and conclusions

If we sum all biotic sinks of atmospheric CO_2 reported herein (Table 5), we arrive at a total of less than 200 Tg C yr^{-1} . For each sink, we feel we have used a reasonable upper limit of the increase in carbon storage that is consistent with our knowledge of the biogeochemistry of forests, rivers and oceans. This sum is small relative to the fossil fuel release of $5000 \text{ Tg C yr}^{-1}$. The reason why biotic sinks are not capable of significantly slowing the atmospheric CO_2 increase via nutrient-matching in the short-term is apparent from a comparison of the stoichiometry of the sources and sinks (Table 1). The burning of fossil fuels and forest harvest and clearing release much more carbon as CO_2 relative to N and P than can be sequestered as organic carbon with this same amount of nutrient in the biotic sinks. Even when other sources of N and P are considered, there is still a large surplus of CO_2 .

A recent summary of the atmospheric CO_2 balance (Woodwell et al., 1983) suggests that the best estimates of CO_2 sources and sinks in (1) result in a residual by differences of between 1000 and $7000 \text{ Tg C yr}^{-1}$. If the discrepancy were $1000 \text{ Tg C yr}^{-1}$ or less, the potential sinks we have discussed in this paper should be examined more intensively. The possibility of increased carbon storage in forests and sediments would then appear to deserve special consideration because of the large potential for storing carbon in forests and marine sediments.

None of the additional mechanism of carbon storage ((a)–(g) in Section 5 of this paper) alter our general conclusion that the biotic carbon sinks are small relative to the rate of CO_2 release from fossil fuel use. As we see the situation, it is a problem of time, not ultimate potential. Man is burning fossil

Table 5. Potential carbon sinks in forests and sediments via nutrient matching

Category	Amount (Tg C yr^{-1})
Forest vegetation and soils due to N fertilization	100
Coastal sediments due to erosion and eutrophication	50
Open ocean due to N fertilization	40
	190

fuels much more rapidly than they are formed. Man is also reducing the stocks of organic carbon held in forests and their soils. Thus the possibilities for short-term storage of excess CO₂ in forests are being reduced. Simultaneously, man is redistributing the stocks of nitrogen and phosphorus; the general trend is for the flow to be from the land to the oceans. A continuation of these trends of depletion of the nutrient stores on land along with other human activity could eventually lead to what might be termed the ultimate eutrophication problem, i.e., a widespread increase in open ocean productivity. Over a very long period, 10³ to 10⁴ years, humans could conceivably double the levels of NO₃ and PO₄ in the deep ocean waters. These waters supply nutrients to the surface plankton communities and the activity of these communities controls the levels of dissolved CO₂ at the ocean surface (Baes, 1982). More nutrients mean lower partial pressure of CO₂ and a more effective oceanic CO₂ sink. Similar interpretations of the linkages between plankton activity, atmospheric CO₂, and glaciations have

been presented by Broecker (1982) and McElroy (1983). The opposing scenario of a reduction in surface ocean productivity caused by toxic substances could conceivably occur much more rapidly and would lead to an increase of surface ocean CO₂ partial pressure and a positive feedback or more rapid increase in atmospheric CO₂ levels.

7. Acknowledgements and dedication

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