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SHORT CONTRIBUTION

On organic soil carbon and CO_2

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ABSTRACT

Cultivation of virgin lands released about 150×10^{12} kg of carbon as CO_2 to the atmosphere during the last 100 years, at rates of 1 to 2×10^{12} kg/yr. These rates exceeded the CO_2 evolved from fossil fuel combustion until the mid-1960s. Soil organic carbon, in organic and mineral soils, may play a considerable role in the CO_2 cycle and in controlling the CO_2 concentration of the atmosphere.

1. Introduction

Baes et al. (1976) reviewed the CO_2 cycle between the atmosphere and the earth's surface and concluded that combustion of fossil fuels was responsible for the CO_2 increase in the atmosphere. Deforestation (Pearman, 1977) and biomass changes generally (Woodwell et al., 1978) may also be a source of CO_2. Stuiver (1978) estimates that the decrease in live and dead biomass amounts to 1.2×10^{12} kg/yr of carbon added as CO_2 to the atmosphere during the period 1850–1950.

The cultivation of virgin lands is a less obvious source of anthropogenic CO_2. Soils rapidly lose 1/2 to 1/3 of their native organic carbon content after initial cultivation due to increased microbial activity and lessened biomass input (Russell, 1961). The fraction lost depends on the intensity of cultivation. The soil's new organic carbon content remains rather constant until management practices change. Revelle (1966) estimated that the CO_2 released by cultivation of virgin lands in the last 100 years is 30×10^{12} kg. This is only 5% of the CO_2 in the atmosphere and was considered insignificant compared to the CO_2 produced by fossil fuels. Revelle's estimate was based on the then-current estimate of organic soil carbon, which may be too low (Bohn, 1976). This paper is concerned with a more detailed estimate of CO_2 released by soil cultivation and of CO_2 removal by carbon accumulation in organic soils (peats).

2. Method

The rate of CO_2 production from cultivation of virgin lands is the product of (1) the annual population increase, (2) the per capita cropland at that time, and (3) the fraction of soil organic carbon lost per unit area by cultivation. Population figures are taken from Deevey's (1971) curves.

The per capita cropland in 1850 was about 8000 m^2, the quotient of 9×10^6 km^2 cropland (Revelle, 1966) and 1.4×10^9 population. The per capita cropland in 1970 was about 4000 m^2, the quotient of 14×10^6 km^2 cropland (Revelle, 1966) and 3.5×10^9 population. The cropland requirement during that time period was assumed to change inversely with the derivative of population growth. This assumption tends to account for the increase in technology and fossil fuel consumption that brought about the relatively recent decrease in per capita cropland.

The average organic carbon content of the world's mineral soil is about 14 kg/m^2, derived from Bohn (1976) by excluding organic soils.

Organic soils were excluded because the location of most of the world's peat and marsh land precludes cultivation. Including all mineral soils as potentially arable tends to make the model conservative. Even so, the 14 kg/m^2 value is slightly higher than the soil organic carbon contents in the potentially-arable soil groups reviewed by Schlesinger (1977). His average organic carbon content of temperate and tropical grassland soils is 10 kg/m^2 and reflects his more conservative values.

The fraction of soil organic carbon lost due to cultivation is about 1/3 when the crop rotation sequence involves fallowing (Russell, 1961). More intensive cultivation, fertilization, and omission of fallowing increase the fraction of carbon lost to 1/2. Beginning about 1940, all newly cultivated virgin land is assumed to be intensely cultivated. By 1950, 5% of the previously cultivated land is assumed to have been converted to the non-fallow cultivation of the 'green Revolution"; by 1960, 15%, by 1970, 25% and by 1980, 35%.

3. Results

Fig. 1 shows the annual rate of carbon released as CO_2 by cultivating virgin soils since 1870, according to the above model. The annual rates rose gradually with population until the 1940s and then rose more rapidly as fallowing diminished. The annual rates of 1 to 2 $\times$ 10^{12} kg/yr from 1870 to 1980 are within range of 1 to 5 $\times$ 10^{12} kg/yr estimated by Bolin (1977) and are slightly greater than the sum of soil plus biomass carbon of 1.2 $\times$ 10^{12} kg/yr estimated by Stuiver (1978).

Fig. 1 also shows the annual rate of carbon from fossil fuel combustion and the annual rise of atmospheric CO_2 in the last several decades. The CO_2 values are derived from an assumed CO_2 concentration of 290 p.p.m. (v/v) prior to 1930. The predicted rate of CO_2 production from soil cultivation exceeded the CO_2 from fossil fuels until the 1960s.

This model indicates that the total CO_2 evolved by cultivation during the past 100 years is about 150 $\times$ 10^{12} kg of carbon; Bolin's (1977) estimate is 10 to 40 $\times$ 10^{12} kg. Extrapolating back 800 years when the last surge in human population occurred (Deevey, 1971) and assuming that the change from shifting cultivation to permanent cultivation (i.e., from no net loss of soil organic carbon to 1/3 loss) prior to 1870 was linear with time, cultivation by

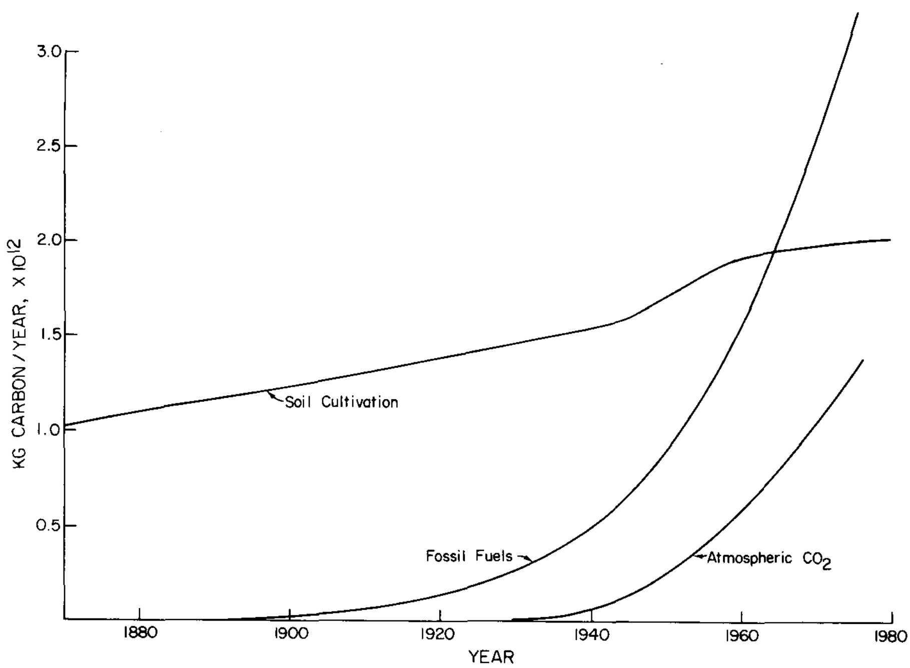

Fig. 1. Annual rates of CO_2 inputs from soil cultivation and from fossil fuel combustion and of CO_2 accumulation in the atmosphere.

1870 had released an additional 180 × 10^{12} kg of carbon.

4. Discussion

The rise in atmospheric CO_2 closely follows the rate of fossil fuel combustion. The CO_2 from soil cultivation and other sources (Stuiver, 1978) has had little apparent effect on atmospheric CO_2 in recent decades. The output from soil cultivation has been substantial for at least two centuries.

This estimate of CO_2 from soil cultivation indicates that mechanisms which remove atmospheric CO_2 are larger than previously realized. One rarely considered removal mechanism is that non-cultivated soils can accumulate dead biomass as soil organic matter. Ancient evidence is the fossil fuel deposits which are, in part, former accumulations of soil organic matter. More recent evidence is the organic-rich layers found in buried soils.

At present, carbon is being amassed in organic soils. Organic (peat) soils are accumulating at an average rate of 1 mm/yr (Twenhofel, 1939; Moore and Bellamy, 1974). This corresponds to a carbon removal rate of 0.4 × 10^{12} kg/yr from the atmosphere (the product of 3.3 × 10^6 km^2 of wetlands (Deevey, 1971), 0.2 g/cm^3 volumetric bulk density of peat, and 0.58% carbon content of peat).

Mineral (<20% soil organic matter, by mass, in surface horizon) soils are also capable of accumulating organic carbon, despite the common assumption that their carbon content is a steady state. Whether mineral soils are now at a steady state, however, is difficult to determine. The mass of soil organic carbon is large enough (Woodwell et al., 1978) that changes in soil carbon content well below the limit of conventional analysis could affect the CO_2 concentration greatly. The 2 or 3 × 10^{12} kg/yr of carbon presently being removed from the atmosphere is only 0.1% of the mass of soil organic carbon.

One example of carbon accumulation by mineral soils is the soil areas which were covered during the last Ice Age. Assuming 10^7 km^2 area (Schuchert and Dunbar, 1931), a soil carbon content of 14 kg/m^2, and a linear accumulation rate, their present carbon content represents 140 × 10^{12} kg carbon accumulation over the last 10,000 years or 0.014 × 10^{12} kg/yr. Most of this carbon accumulation was not net removal from the atmosphere. The warmer climate causing the northward movement of glaciers, wetlands, and forests also oxidized the soil carbon which had accumulated along the southern edge of the glaciers during the glacial advance. Whether these and other mineral soils are continuing to store carbon from the atmosphere is uncertain.

Organic and mineral soils are large potential sinks for carbon. Beyond the buildup of peat soils, however, the role of soil organic carbon in controlling present-day fluctuations of atmospheric CO_2 is unclear. Stuiver (1978) considers the oceans to be a large carbon sink so that the annual carbon stored by non-cultivated and uncleared mineral soils worldwide, if operative, would be less than 0.01% of soil's organic carbon content.

Soil organic matter may be largely ignored in CO_2 discussions because the mass of soil organic carbon is falsely assumed to be closely related to biomass. Actually the amount of soil organic carbon is rather independent of biomass and net primary productivity and depends much more on the rate of microbial decay. For example, organic soils are found in parts of the Amazon Basin, the Arctic tundra, and above the tree line in the Alps, although these regions differ widely in biomass and productivity. The low decay rates in these soils are due to low oxygen diffusion through water-filled soil pores. Well-drained soils in these same regions contain much less organic carbon because of adequate oxygen transfer. A second potentially important distinction between soil organic carbon and biomass is their response to climate. Soil organic carbon increases with increasing rainfall and with decreasing temperatures regardless of the climate effect on biomass.

Although organic carbon may be accumulating as sediments in lakes and oceans due to higher nutrient availability (Stuiver, 1978), inorganic fertilization has the opposite effect on soils. Fertilizers stimulate the soil's microbial decomposer population to further deplete soil organic carbon. This effect exceeds the greater biomass production from fertilization.

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