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Biological cycling of CO_2

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SUMMARY

The present rate of fossil fuel consumption is equal to one tenth of the rate at which carbon is naturally cycling through the biosphere. In the present situation, biomass has only a modest potential to partly replace fossil fuel as an energy source.

INTRODUCTION

The Major Carbon Fluxes

The atmospheric CO_2 content (presently 350 µmol mol^{-1}) rises at a rate of about 1.8 µmol mol^{-1} a^{-1}, mainly due to the use of fossil fuel, and to a much lesser extent to deforestation. When considered on a decadal time scale, a few major reservoirs of carbon are involved (Figure 1): the atmosphere (700x 10^{15}g C, or 700 Gt C), the oceans (39000 Gt C), the terrestrial biosphere (2000 Gt C), and the fossil fuel reserves (6000 Gt C) (Bolin et al.,1979). At present the rate of burning of fossil fuel amounts worldwide to 6 Gt C a^{-1}, and the rate of carbon release as a result of deforestation to a figure between 0 and 2 Gt C a^{-1}. Ocean and atmosphere exchange CO_2 by molecular diffusion, at a rate of about 60 Gt C a^{-1}. Photosynthetic activity of plants drives the carbon flux from atmosphere to biosphere at a rate of about 50- 60 Gt C a^{-1}. Respiration and decomposition recirculate this flux almost entirely to the atmosphere. Tapping this biospheric flux is a potential means to reduce fossil fuel consumption.

PHOTOSYNTHETIC CARBON FIXATION

Carbon in Organic Material

Life on Earth can be considered as carbon-based. Living material is a mixture of a large portion of water without which life cannot function and a much smaller portion of dry matter containing 45 to 60% carbon. No other element than carbon has such a stable presence in living material.

Ultimately almost all life on Earth is based on solar energy, captured by green plants and

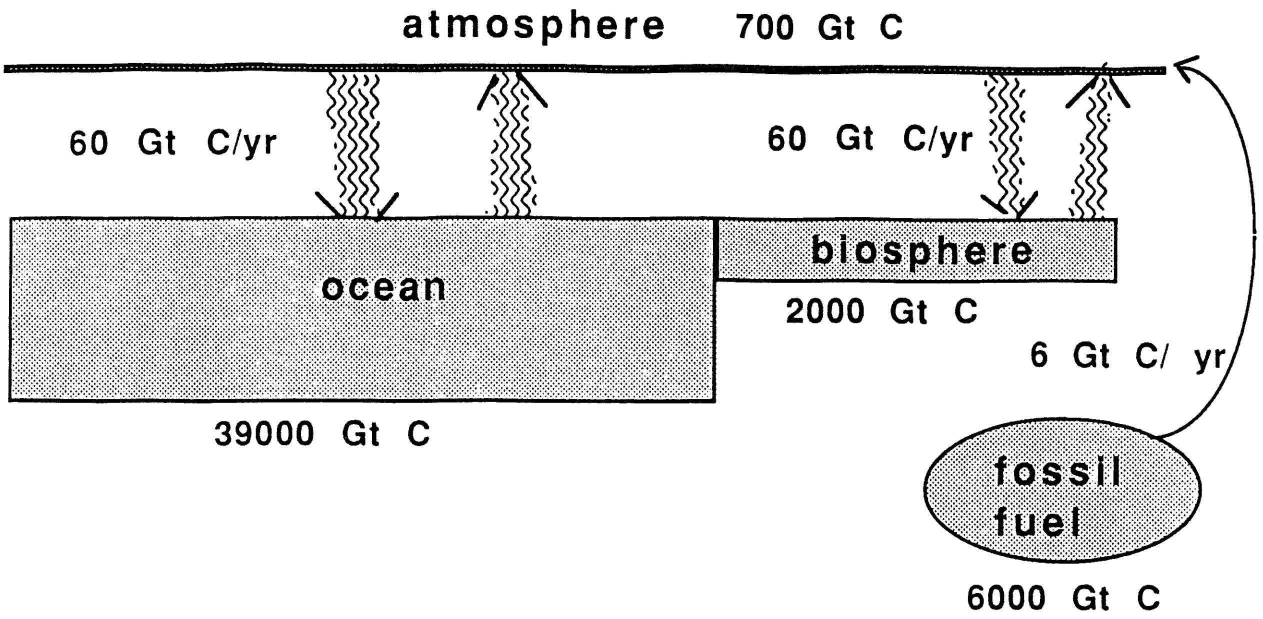

Figure 1 Major global carbon pools and their exchange fluxes

utilized in the process of photosynthetic carbon fixation. In this process atmospheric CO_2 is taken up from the air and transformed into glucose. Carbon is the only element in living material that must be taken up from the air. Its fixation into living plant material that has a carbon concentration of about 50% is quite an achievement, in view of the extremely low concentration of CO_2 in the atmosphere of only 350 μmol mol^{-1}.

The product of this photosynthetic activity -glucose- is an energy carrier in the first place, but it is also the raw material for living matter. From the leaves it is transported to other plant organs for transformation into essential substances such as proteins, lipids, and lignin in cell walls. It may be transformed into other carriers of energy such as sugars (e.g. in sugar cane or in sugar beet), starch (potato, cassave), or lipids (oil palm, sunflower, rape seed). The food web of animal life is ultimately based on plant material.

Energy Efficiency of Photosynthesis

The spectral range of photosynthetically active radiation (PAR) covers 400 to 700 nm wavelength, practically identical to the range of human visual power. About 45% of incoming solar radiation is within this range. For PAR the reflectance of vegetated surfaces amounts to about 5 to 10% , but for longer wave lengths (Near Infra-Red, 700-2000 nm) the reflectance sharply rises to about 40%. Bare soil reflects between 10 to 20%, and does not exhibit this sharp transition.

When operating at the theoretically maximum efficiency, the photosynthetic machinery needs 8 photons to reduce one molecule of CO_2 : a so-called quantum yield of 0.125 (Björkman,1966). For an average wavelength of 550 nm (green), this ratio corresponds to an energy efficiency of 27% . Several factors reduce this efficiency. First, in green leaves not only chlorophyll, but also other non-photosynthetic material absorbs radiation, reducing the potential efficiency to about 20%. Second, photorespiratory losses, caused by high atmospheric content of oxygen in comparison to that of CO_2, bring it further down to about 13%, although rising atmospheric CO_2 can suppress this type of loss (Goudriaan et al.,1985). This efficiency of 13% is the value that is actually measured in green healthy leaves under low irradiation. Third, the photosynthetic rate of leaves is saturated above about 100 W m^{-2} of PAR, which decreases the efficiency strongly. Fourth, respiratory losses amount to about 40% of the gross carbon fixation . The mean efficiency for a crop stand growing in optimal conditions arrives at 6% of PAR intercepted by the leaf canopy.

ANNUAL GLOBAL CARBON FIXATION

Theoretical Potential

The global mean of irradiation of PAR at ground level is about 7 MJ m^{-2} d^{-1}, and the chemical energy content of carbohydrates about 39 kJ per gram of carbon. At an energy efficiency of 6%, a daily carbon fixation of 10.8 g C m^{-2} d^{-1} is possible, or 3.9 kg C m^{-2} a^{-1}. This figure of 10.8 g C m^{-2} d^{-1} corresponds well with De Wit's rule of thumb for a potential growth rate of 200 kg of dry matter per hectare per day (De Wit et al.,1979). For the total planetary area on Earth of 510×10^{12} m^2 this results in a potential annual carbon fixation of 2000 Gt C a^{-1}.

Actual Estimates

Carbon fixation in natural ecosystems can be estimated from the growth of new plant material throughout the year (Reichle et al.,1975). With increasing maturity of an ecosystem, a larger fraction of this so-called Net Primary Productivity (NPP) is used by grazing animals and microbes, more carbon being recirculated and less being sequestered. Measurements of NPP are hard to make because carbon can cycle quickly through the ecological system . The presently accepted actual value for terrestrial carbon fixation is only one tenth of the potential level and is estimated at about 50-60 Gt C a^{-1}(Lieth at al.,1975; Ajtay et al.,1979). This figure is much lower than the theoretical estimate, first because radiation is lost in deserts and other non-vegetated surfaces, second because in mature ecosystems respiratory losses are higher than in crops, third because photosynthetic activity is reduced by seasonal drought, unsuitable temperatures and nutrient shortage, and fourth because even in optimal agricultural circumstances the land is periodically bare for the purpose of soil cultivation. The portion of agricultural land in global NPP is about 8 Gt C a^{-1} , of which only 0.3 Gt C a^{-1} is directly eaten by man. This strong reduction in carbon flux is due to fodder-meat conversion (about 10:1), to non-food crops being included in agriculture, and to losses in harvest, storage and preparation of food.

Marine NPP was estimated at 40 Gt C a^{-1} by De Vooys (1979), which is an even much smaller fraction of the potential level than on land, mainly because plankton growth is severely nutrient limited. About one tenth of this flux sinks down to intermediate ocean depths where decomposition gives rise to the high CO_2 contents of deep ocean water (above 1000 µmol mol^{-1}; Baes et al.,1985). In the upper layer of the sea, plankton growth causes an extraction of carbon from the water, and strongly reduces the levels of nutrients such as phosphate. Local upwelling of deep water returns these nutrients and also some of the accumulated carbon to the surface layers. The intensity of this carbon circulation flux is estimated to be about 3 Gt C yr^{-1} .

Chemical buffering of CO_2 in the ocean

With industrialization, increasing amounts of CO_2 from fossil fuels are being released into the atmosphere, at present at a rate of 6 Gt C a^{-1}. The chemical equilibration of ocean water with atmospheric CO_2 is the most important sink of CO_2 released into the atmosphere, whether from fossil fuel or from the biosphere. The fraction remaining in the atmosphere, the so-called 'airborne fraction', can be estimated from the measured rate of increase of carbon in atmospheric CO_2 versus CO_2 release due to the use of fossil fuels. Over the period 1960-1980 this fraction had a value of about 0.58 (Bolin, 1986). The airborne fraction is dependent on the rate of emission of CO_2 into the atmosphere. A lower rate of emission will give more time for absorption in the ocean. The chemical buffering capacity of the oceans is large enough for about 85 % of each unit of CO_2 emitted into the atmosphere to be absorbed eventually, leaving only 15% in the atmosphere. However, CO_2 emission grows much faster than mixing in the deep sea can accomodate. In fact, hundreds of years would be needed for this absorption capacity to be fully utilized.

Buffering of carbon in the terrestrial biosphere

The pool of carbon of the terrestrial biosphere is modest when compared to the amount in the ocean. Still, an undisturbed biosphere is potentially able to sequester large amounts of carbon (Lugo and Brown,1986). Significant amounts of carbon (mainly in the form of CO_2) can be released from the biosphere when it is disturbed (Houghton, 1986). Reclamation of land for agriculture and for other types of human utilization can cause oxidation of carbon compounds in the soil and of long-lived biomass such as wood. Such processes did occur during the past century, and are still accelerating now, mainly in the tropics. Regrowth on abandoned land partially compensates for losses of carbon elsewhere. At the same time increased atmospheric CO_2 itself acts as a global stimulus to plant growth, thereby partly compensating the disturbance of the biospheric carbon balance (Lemon, 1984; Goudriaan and Ketner, 1984; Goudriaan,1989). This stimulation of net photosynthesis by CO_2 causes an additional buffering of atmospheric CO_2, up to about one fifth of the buffering capacity of the oceans.

PROSPECTS FOR ENERGY FROM BIOMASS

Energy carrying carbohydrates cannot simply be drained from the plants without damaging them, because plants must be harvested. Plant material always contains nutrients such as nitrogen which are essential for growth, but which must be considered as contaminants when the plant material is used as a fuel. Traditional agricultural species have usually been bred for purposes in which high protein content is desirable. New agricultural systems will have to be developed that maximize the carbon harvest at minimal nitrogen content. For competitiveness with fossil fuel, such systems should be labour extensive. Land requirement will be considerable and is of the order of at least 1 km^2 per MW of electrical power fuelled, even in good agricultural circumstances. This figure includes a loss of a factor three for the conversion from thermal to electrical energy.

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