Chemical and Energy Balances in Nature

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The biosphere can be considered a closed system in which there is recycling of the chemical elements between living matter (biomass), the atmosphere, the hydrosphere, and sediments. Chemical analysis of biomass gives an average chemical composition of $C_5H_7N_2O$; the elements C, H, N and S are of particular interest because the exchange between the various spheres is global. Other elements (Fe, P, Mg, Mn, Mo, Co, Cu, Zn, Ca, Na, K) recycle between biomass and the environment, but only in restricted zones (e.g., individual lakes and farming systems) because of the lack of gaseous or easily volatilised derivatives of these elements.

Through the recycling of elements in a closed system over the long period of time that biological systems have existed (three billion years), a steady-state exists which is now slowly changing because of the advent of industrial man. A change in the steady-state could have disastrous effects on the environment if allowed to accelerate, and would result in the destruction of the biosphere as we know it. The result could be the absence of man and most plants - replaced by a world of microorganisms and a few hardy higher organisms, insects, etc. One of the indications of the change in the steady-state is the carbon dioxide concentration in the atmosphere and the associated reactions involved in the carbon cycle.

THE CARBON CYCLE AND THE SUNLIGHT TO CHEMICAL ENERGY TRANSDUCER

The analysis of readily exchangeable C reveals that 24% exists as CO_2 in the atmosphere and hydrosphere, 74% as organic matter being decomposed with the aid of microorganisms, and 2% as growing plants and animals (Bolin, 1971). The primary energy input for the biosphere comes from the sun. The mechanism of transducing light to chemical energy is called photosynthesis and is catalysed by chlorophyll-containing plants (algae and leafy plants). Chlorophyll is green and is the transducing molecule. About 99% of the photosynthesizing plants exist on land in the form of forests and grasslands, with the remaining 1% in the form of phytoplanktonic algae in the oceans. Photosynthetic activity is equally divided between land and water systems and can be represented by equation (1):

$$CO_2 + 2H_2O \xrightarrow{\text{light}} \underset{\textit{biomass}}{[CH_2O]} + H_2O + O_2 \qquad (1)$$

The result of photosynthesis is the formation of new biomass at the expense of CO_2 and light energy, and the production of oxygen from water.

In the case of animals and microorganisms, the only source of carbon dioxide available is the oxidation of carbon compounds present in or derived from the biomass. The oxidation process is called respiration and can be represented by equation (2):

$$[CH_2O] + O_2 \longrightarrow \begin{array}{l} CO_2 + H_2O \\ + \text{ biological energy} \end{array} \qquad (2)$$

Consequently animals and microorganisms need organic compounds to satisfy two functions: (a) production of energy required for movement, heat, maintenance and synthesis of new biomass; (b) supply of organic compounds for the synthesis of new biomass. That's why you eat.

Microorganisms are the major contributors to the breakdown of organic compounds to carbon dioxide and water; microbial examples include the oxidation of crude oil, and the breakdown of lignin (a major component of trees) and chitin (hard shells of insects and seafood). Many carbon compounds (e.g. chlorohydrocarbons) are refractory; a compound previously thought to be biologically refractory is carbon monoxide, but it has recently been shown (by the Queen's University Department of Biology) to be oxidized to carbon dioxide by plants.

In the steady-state concept of the biosphere, reactions (1) and (2)

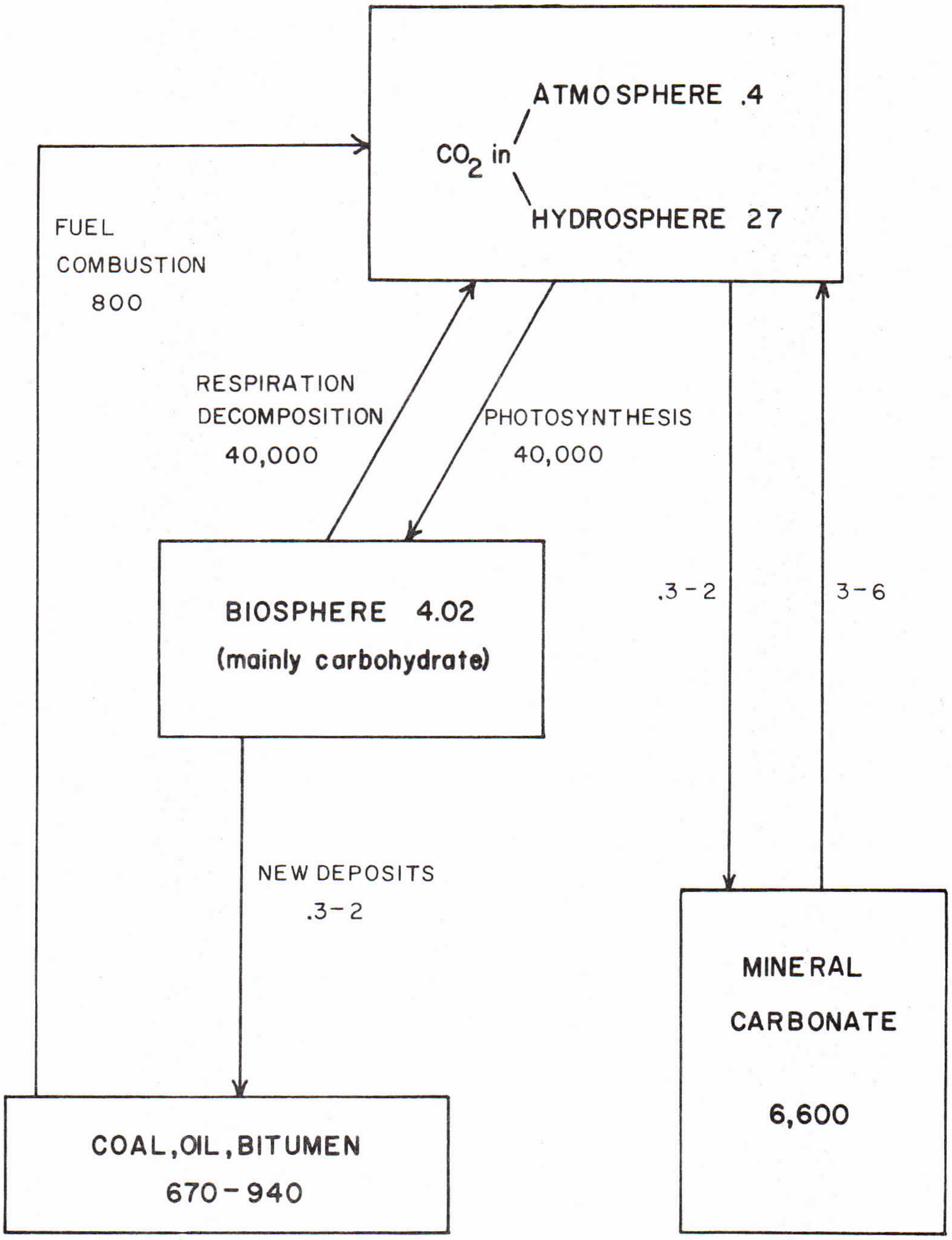

FIGURE 1. THE CARBON CYCLE
Values in boxes are grams of carbon per square centimeter of earth surface.
Values on arrows are micrograms of carbon per square centimeter of earth surface per year.
(Data from Brock, 1966).

should be balanced. An indicator of this is the carbon dioxide content of the atmosphere which in 1968 was 320 parts per million away from industrial areas in Antarctica and the Arctic, and is increasing at the rate of 0.7 parts per million per year (SCEP report, 1970). Because this concentration is increasing, an imbalance exists between reactions (1) and (2). This change could be due to the following phenomena.

Industries, through the oxidation of carbonaceous fuels, are generating carbon dioxide - Bolin (1971) estimates that the industrial CO_2 output is 14% of the output from respiration. The rate of photosynthesis is linearly dependent on CO_2 concentration in the range 200 to 1000 parts per million, and therefore one would expect reaction (1) to accelerate to compensate for the increasing carbon dioxide concentration in the atmosphere. As this result has not been observed, another factor must be limiting reaction (1), such as light, availability of nutrients and water, or concentration of photosynthesizing biomass. Since the majority of land plants exist in forests, the cutting of trees without adequate replacement would result in the slowing of reaction (1). Such destruction of trees occurs in the Brazilian jungle (Johnson, 1972). Another important concern is the effect of chlorohydrocarbons and other pollutants on the photosynthesis of phytoplankton, and the use of defoliants. Changing styles of living and associated farming changes result in the slowing of reaction (1). Concomitant with the destruction of plant life is the increased rate of respiration (2) by the microbial decomposers which are not affected by pollutants. The combined influences of all these forces and probably other unknown ones on reactions (1) and (2) result in a change in the atmospheric carbon dioxide content. Carbon dioxide can therefore be an indicator of the health of the biosphere and the existence of the necessary steady-state condition. Subsidiary and dependent on the carbon cycle and the interconverions of energy forms are other elemental cycles.

THE NITROGEN CYCLE

$$N_2 \xrightarrow{1} \text{Biomass N} \underset{2b}{\overset{2a}{\rightleftharpoons}} NH_3 \underset{3b}{\overset{3a}{\rightleftharpoons}} NO_3^- \xrightarrow{4} N_2$$

The majority of nitrogen in this cycle exists as dinitrogen in the atmosphere; ammonia and nitrate in global terms are evanescent compounds, but in the local environment of man are important compounds for the nutrition of plants (crops and polluted lakes).

Reaction steps 1, 2b, 3b and 4 require an energy source, the nature

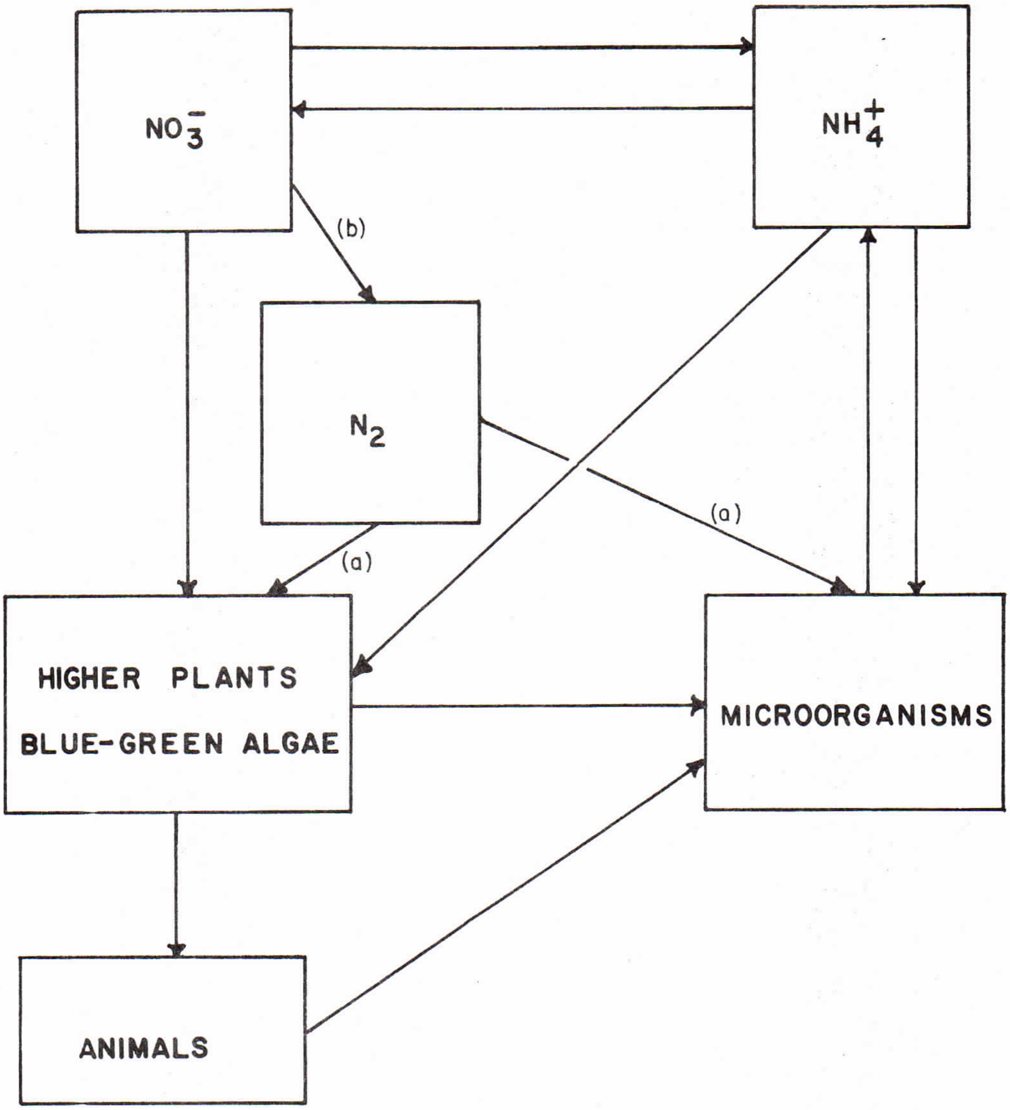

FIGURE 2. THE NITROGEN CYCLE
(a) Dinitrogen fixation
(b) Denitrification

of which depends on the organisms catalysing the reactions. Step 1 is known as nitrogen fixation and is catalysed by (1) Haber process, operated by man, (2) Light-dependent processes, operated by blue-green algae (3) Processes dependent upon the decomposition of carbon compounds, operated by free bacteria present in soil, water, and even guts of New Guinea natives, and by symbiotic bacteria in association with plant roots, for example, nodules of legume plants (peas, beans, clover, etc.), trees (ginkgo and alder) and bulrushes. The incorporation of inorganic nitrogen into biomass by steps 3a and 3b is carbon compound-dependent and the basis of increased crop yields through the addition of fertilizers. The return of nitrogen (step 4) to the atmosphere is carried out by denitrifying bacteria present in soil and stagnant waters, and requires carbon compounds as a source of energy. Reactions 2a and 3a are energy-generating. Step 2a is catalyzed by animals and microorganisms and step 3b by microorganisms. In the cycle there is a negative feed-back loop: ammonia can slow down step 1, but because of the slow distribution of ammonia throughout the environment its effect is localised.

Again the steady-state concept applies to this elemental cycle and the indicator compounds would be ammonia and nitrate. The imbalance in the cycle is caused by the addition of fertilizers in the form of ammonia or compounds which decompose rapidly to yield ammonia. This could be alleviated by the use of slowly decomposing nitrogenous compounds such as exist in compost.

SULPHUR CYCLE

$$\text{Biomass S} \underset{1b}{\overset{1a}{\rightleftharpoons}} H_2S \xrightarrow{2} S \xrightarrow{3} H_2SO_4 \xrightarrow{4} H_2S$$

All the reaction steps are microbial and necessary for the recycling of sulphur. Animals and plants catalyze reactions 1b and 4, and man catalyzes reactions 2 (Alberta sulphur stockpiles) and 3 (combustion fuels containing sulphur). Accumulation in the environment of intermediates in the sulphur cycle is very obvious and harmful.

OTHER ELEMENTAL CYCLES

These cycles can be generally represented by the equation

$$\text{Biomass (E)} \rightleftharpoons \text{(E)},$$

where E is phosphate, metals Fe, Mg, Mn, Zn, Mo, Co, Cu (all necessary for life) and toxic metals Hg, Cd, As, Cr, Ag, Be, Sr, Ba, etc. These elements can exist combined with living matter, or as free and/or insoluble entities; the exchange between the two states is in most cases facilitated by microorganisms. An example is the conversion of insoluble mercury or phosphate compounds in lake sediments to a soluble form by bacteria (SCEP Report, 1970, and *Scientific American*, September 1970).

ELEMENTAL CYCLES IN CANADA

All the cycles discussed operate in Canada, but many interconversion reactions are slowed down or even eliminated by cold temperatures. The result is that Northern Canada is relatively infertile because of the absence or limitation of nitrogen fixation and such elements as S, Fe, P, etc. The only documented studies on elemental cycles in a cold climate indicate the presence of a variety of algae growing in Antarctica, including a blue-green algae found to fix dinitrogen in the summer months (Bunt 1971). Elemental cycle data is required for Canada in order to enable assessment of the development of this country.

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