Major Biogeochemical Cycles and Anthropogenic Changes

by Robert Cook

Carbon, nitrogen, phosphorus, and sulphur are needed for the formation of the fundamental molecules on which life depends. However, living organisms have in turn modified the primordial distribution and circulation of these elements. Thus, the biogeochemical cycles that are so crucial for maintenance of life on earth are themselves largely determined by biological processes. Human activity is now generating fluxes of C, N, P and S comparable in magnitude to natural fluxes, thereby upsetting the delicate balance that existed until recently.

Background

The major biogeochemical cycles of carbon, nitrogen, phosphorus and sulphur are significantly influenced by human activity. For example, the use of natural resources is accompanied invariably by the production of unwanted wastes (Fig. 1). The burning of coal and petroleum releases C, N, and S compounds into the atmosphere, and increasing atmospheric CO₂ may cause a significant warming of global climate. Nitrogen and sulphur emissions have been linked to the formation of acidic rain and snow, which can have harmful consequences for some sensitive ecosystems. The use of nitrogen and phosphorus fertilizers may result in significant pollution of rivers, lakes, and coastal waters. The natural cycles of C, N, P, and S must be understood in order to analyze the long-term impact of these wastes on the atmosphere, oceans, and freshwater and terrestrial ecosystems. Though natural resources such as soil, vegetation and water can be renewable, with increasing demands for improved conditions from a growing world population these will require careful management.

The natural biogeochemical cycles and their perturbation by man have been the focal point for a study of the global environment by the ICSU Scientific Committee on Problems of the Environment. SCOPE was created by ICSU in 1969 to assemble, review and assess information on man-made environmental changes and their effects on man. The Committee evaluates methods of measuring environmental parameters, and provides an intelligence service on current research, acting for the benefit of research centres and organizations concerned with environmental studies. The ultimate goal of SCOPE is to provide an integrated view of the global ecosystem, so as to assess long-term consequences of the increasing use of the earth's natural resources.

SCOPE's Project on Biogeochemical Cycles began in 1975 with a synthesis of work on the global N, P, and S cycles (Svensson and Soderlund, 1976) and continued with a report on the carbon cycle (Bolin et al. 1979) and another reviewing perspectives on biogeochemical cycles in general (Likens, 1981). More recently a detailed review of important Soviet work on the S cycle has been released (Ivanov and Freney, 1983). The project examined the interactions between major biogeochemical cycles at a workshop held in Örsundsbro,

Figure 1: Processing base metals in British Columbia.

Sweden, in 1981 and attended by geochemists, sedimentologists, oceanographers, as well as microbiologists, terrestrial ecologists, soil scientists, and meteorologists. The present review is based on the workshop's findings as reported in Bolin and Cook (1983; see also Cook, in press).

Natural Biogeochemical Cycles

The biogeochemical cycles of C, N, P, and S under natural conditions can be illustrated by the establishment and development of soil and vegetation on a previously unoccupied site. If new rock materials are deposited following a volcanic eruption or exposed by the melting of a glacier, the new substrate is at first devoid of C and N, though P and S are commonly present in the freshly exposed rock material. The development of plants on such a site initially requires seeds carried to the site by the wind. As the seed grows into a plant, it takes up atmospheric CO₂ by photosynthesis and atmospheric N by nitrogen-fixing micro-organisms. Sulphur can also be supplied from the atmosphere.

As the plants die and decompose, organic matter containing C and N accumulates and increases the fertility of the soil. Soil micro-organisms convert this matter to forms that are readily used by growing plants. Once the availability of N in the soils is high, plants without the capability of fixing this element can grow; thus N-fixation peaks relatively early in soil development.

Terrestrial ecosystems are remarkable for their ability to economize on nutrients by efficient recycling (Wood et al., 1984), none more so than in tropical rainforests growing on ancient and highly leached soils, as in the Amazon basin (Jordan, 1982). However, some nutrients - especially P - can be converted into unavailable forms or leached and removed from the ecosystem by running water. This slow loss is irreversible under natural conditions because there is relatively little replenishment of P from the atmosphere. Thus, as more and more of the nutrients are lost from the soil or otherwise become unavailable, the fertility decreases.

Terrestrial and aquatic ecosystems supply many gases to the atmosphere. Respiration and decay of organic matter are sources of CH₄, CO, CO₂, NO and NO_x. Gaseous sulphur compounds are produced in anoxic environments, as for example H₂S in swamps and bogs, (CH₃)₂S by actively photosynthesizing aquatic plants, and SO₂ from volcanoes. These gases are transported in the atmosphere, from which the elements are returned to the ocean and to terrestrial ecosystems in rain and snow and by dry deposition directly from gaseous phases or settling of particulate matter.

The atmosphere, of course, also plays a decisive role in regulating the temperature at the earth's surface. Without the presence of the atmosphere, average surface temperatures

Figure 2 The global carbon cycle according to Bolin (in Bolin and Cook, 1983). Reservoir sizes (in boxes) and annual fluxes are in 10^{15} g C.

would be about -18°C . However, because the CO_2 , H_2O and O_3 in the atmosphere trap the out-going infrared surface radiation, the mean surface temperature is about 17°C (Walker, 1977). It is interesting to note that the global ecosystem must have developed over geologic time scales in response to climate, which is regulated by trace gases, as well as in response to the supply of nutrient elements from the atmosphere and the lithosphere.

The composition of the atmosphere is strongly influenced by the photochemistry of ozone. Its photodissociation by ultraviolet solar radiation leads to the production of the hydroxyl radical (OH), which reacts with many atmospheric compounds that would otherwise be much more inert and abundant. For example, OH reacts with methane and carbon monoxide to yield CO_2 . It also oxidizes nitrogen oxides, SO_2 and reduced S compounds to form nitric and sulphuric acids.

The global circulation of C, N, P and S is also associated with the hydrologic cycle, beginning with the solar evaporation of water and the dispersion of water vapor into the atmosphere. Part of the water is deposited upon the continents and enters the oceans through rivers, coastal run-off and subterranean discharge, and part enters the ocean directly as rain or snow. Atmospheric and terrestrial waters are continuously undergoing chemical alteration along their way to the oceans, by processes such as gas dissolution in the water droplets of the atmosphere, biological activity in rivers, and continental erosion.

The chemical composition of rivers is determined by a number of factors, such as the nature of the geologic substrate and the character of vegetation in the drainage basin, and hydrographic conditions such as flooding. Mixing of riverine waters with the sea takes place in the estuarine zone where, depending largely on the hydrodynamic properties of the estuary, chemical and biological processes may profoundly change the speciation and the transfer of elements to the adjacent coastal zone. Where fresh water meets salt, flocculation and sedimentation remove part of the riverborne organic matter and some dissolved inorganic species. The decrease in turbidity associated with these processes and the consequent increase in sunlight penetration promotes high

algal productivity in places where nutrients are in high supply. The nutrients are then transferred from solution to particulate organic matter and may settle to deeper waters or in bottom sediments. Microbial activity in the sediments in turn decomposes this organic matter to its component nutrients, which may then be released back to the overlying waters.

The coastal zone, bounded by the 200 metre isobath and the continents, receives the material transported by the rivers and estuaries. About 90% of the organic matter that reaches and is buried in the ocean floor passes through this zone, which accounts for about 25% of the primary productivity of the oceans.

The open sea is by far the largest reservoir for C, N, P and S, and because of this size the sea responds slowly to imposed disturbances. Photosynthesis here is limited to the top 100 metres. The chemistry of some elements in the sea, most notably C, N, O, P and perhaps Si and Al, is strongly mediated and linked by the biota. Algae in the sea incorporate these elements in fixed proportion, thus controlling their abundance. Photosynthetic organisms are very efficient in utilizing available nutrients and rapidly recirculate much of this material. Because algal growth is limited by the supply of P, most is found in organic matter and little inorganic P exists in solution. A small fraction of the organic matter does settle out, mostly as fecal material and as dead organisms large enough to sink to the ocean floor.

The transport of C, N, P and S from the atmosphere to the oceans takes a few years to a few decades. However, once these nutrients have been incorporated into ocean sediments many millions of years will pass before they are brought back to the earth's surface as, for example, sedimentary rocks or as fossil fuel. The length of time for the nutrients to move through this system is clearly important for predicting how quickly human activity will affect the various cycles.

Thus, after life developed on earth, the global distribution of C, N, P and S was established by the interplay of biological, chemical, and geological processes and transport by wind and water. With the accelerated use of natural resources in the industrial era, human activity has also become a factor.

Human Influences on the Biogeochemical Cycles

The global carbon cycle is illustrated in Figure 2 (Bolin, in Bolin and Cook, 1983). Emissions to the atmosphere from combustion of fossil fuels (5×10^{15} g per year) and from deforestation ($1-2 \times 10^{15}$ g per year) are partly balanced by an annual gas transfer into the ocean of $1.5-2.5 \times 10^{15}$ g and by a yearly increase in atmospheric CO_2 of 3×10^{15} g. The mass of carbon in the atmosphere has increased by about 80×10^{15} g since pre-industrial times (Bolin, in Bolin and Cook, 1983). Between 1860 and 1980, deforestation may have contributed about 180×10^{15} g (Houghton et al. 1983), although revised assessments of the mass of carbon stored in forests suggests the actual value is lower by as much as half (Brown and Lugo, 1984). These uncertainties raise questions about the role of the terrestrial biota in the global carbon budget.

The main sources of CO_2 to the atmosphere are bacterial decomposition of organic matter, gas exchange in the ocean, deforestation, respiration by animals, and the burning of coal and petroleum (Fig. 2). The annual release of CO_2 to the atmosphere from the burning fossil fuels is equal to about

10% of that used during natural photosynthesis by terrestrial plants. This activity is responsible for increasing the CO₂ concentration from pre-industrial values of 270 ppm by volume to 335 ppmv in 1981. Typical estimates of the future combustion of fossil fuels implies that the atmospheric CO₂ concentration will be double our present one sometime in the next century (see Episodes, 1983/4, p. 28), resulting in a global surface air warming of between 1.5°C and 4.5°C (National Academy of Science, 1983a). In addition to CO₂, the atmospheric concentration of nitrous oxide, methane and ozone, all produced by human activity, also appear to be increasing. If so, climatic changes can be expected significantly earlier than predicted for CO₂ alone.

A key to understanding future changes in carbon dioxide and climate is the time frame of change prior to 1958 and the factors causing these changes (National Academy of Sciences, 1983a). Analyses of the air trapped in Antarctic and Greenland glaciers show that the pre-industrial partial pressure of CO₂ was as low as 200 ppm (Nefel et al., 1982). Changes in atmospheric CO₂ have possibly contributed to the climatic variations that have occurred during the last 30 millenia. However, from the available data it is more likely that atmospheric CO₂ responded to climate.

The direct effects of elevated atmospheric CO₂ on terrestrial ecosystems are not well known, beyond the fact that both photosynthesis and growth increase in individual plants that are not strongly limited by light, water or nutrients. The efficiency with which plants use water (the ratio of net primary production to evapotranspiration) is also increased because of the higher CO₂ concentration gradient between plants and leaves. It is not clear, however, that either natural or cultivated plants in the field are limited by CO₂ often enough so that plant growth can be substantially increased in this way (National Academy of Science, 1983a). However, some increase in terrestrial productivity and some limited increase in total biomass is the most likely outcome of higher atmospheric levels of CO₂.

Figure 4:
Estimates of the
global emission
of sulphur from
anthropogenic
sources between
1860 and 1980.
Source:
Tyaboshapko (in
Ivanov and
Frenay, 1983).

Sulphur perhaps more than any other element, exemplifies the difficulties in understanding how wastes disturb the natural cycle. This is illustrated in Figure 3, which shows the annual fluxes from human activity as well as those estimated to have existed earlier. Sulphur in the atmosphere is derived from a number of sources, including volcanoes, the burning of oil and coal, and micro-organism activity in tidal flats and water-logged soil. Recent evidence (Cullis and Hirschler, 1980) suggests that global S emissions from burning fossil fuels may be as high as $118 \times 10^{12}g$ each year, having risen from $17 \times 10^{12}g$ at the turn of the century (Fig. 4). Sulphur gases are converted in the atmosphere to sulphuric acid, which is then conveyed to the earth's surface by precipitation or dry deposition. Many of the effects are identical for S originating from either natural or man-made emissions, and only through careful measurements can their relative importance be determined.

Sulphur emissions to the atmosphere, primarily by burning of coal and petroleum, probably exceed the natural emissions of sulphur gases from volcanoes, swamps, bogs and tidal flats. In industrial regions, emissions of S far exceed those due to natural processes. Sulphur dioxide and other gases have been shown to reduce plant growth near major sites of fossil fuel combustion (Johnson and Siccama, 1983; Tomlinson, 1983). Most terrestrial eco-systems are relatively well buffered, however, and direct toxic effects of increased acidity have been conclusively established in several regions. For example, the toxicity of acidic precipitation has been implicated in an area of Vermont in which 50 per cent of the trees died between 1965 and 1982 (ibid). Acidic precipitation may also cause increased leaching of sulphate and accompanying cations and trace metals by stream water and groundwater in many soils. The increased acidity and metal content of runoff and streams is causing acidification of lakes in Scandinavia, Canada and northeastern United States, with damaging effects on fish and other aquatic organisms.

The nitrogen cycle is intimately coupled to that of carbon, because N is essential for the formation of proteins, an important constituent of living biomass. The atmosphere plays an important role in the nitrogen cycle, because of compounds like N₂, N₂O, NO, and NH₃, which can all be produced and consumed through biotic and abiotic processes (Fig. 5). The industrial production of nitrogen fertilizer will, toward the end of this century, probably become as large as that produced through biological fixation of nitrogen in terrestrial ecosystems. Like the sulphur gases, nitrogen

Figure 3: The global sulphur cycle according to Granat Rodhe and Hallberg (in Svensson and Soderlund, 1976). Annual fluxes in 10¹²g. Bold figures are estimates of contributions from human activity and the light figures denote fluxes before man influenced the cycle.

Figure 5: The global nitrogen cycle according to Soderlund and Rosswall (1982). Yearly fluxes are 10^{12} g.

oxides react in the atmosphere to form acidic compounds, which contribute to acidic wet and dry deposition.

The amount of N, as nitrogen oxides and nitrate, formed by the burning of coal and petroleum and also by fertilizer manufacturing is equal to about one-half of that produced naturally by the biosphere. The N emitted to the atmosphere during combustion of petroleum and coal returns to the earth's surface in precipitation or by dry deposition. This could help to fertilize areas where terrestrial productivity is limited by the supply of nitrogen.

Such an effect might be significant over considerable areas, but conclusive evidence for any change in forest productivity in this way is lacking. If forest biomass is increased by additions of N from the atmosphere, some of the CO_2 released by fossil fuel emissions could accumulate in the increased biomass. One estimate of the maximum potential accumulation of C in this pool is 5-10% of the total C released by combustion (Melillo and Gosz, in Bolin and Cook, 1983).

Unlike C, N, and S, phosphorus does not have a significant gaseous phase in the atmosphere (Fig. 6). Atmospheric P occurs largely in the form of aerosols that originate from crustal weathering, the ocean, and human activity. The major impact of man on the phosphorus cycle is through the necessary use of P fertilizers, which arises when the P in soil is naturally low or when it has been depleted due to intensive farming. Phosphorus is eventually removed by air or water transport to the ocean, where it is taken up by organisms and eventually incorporated into bottom sediments and after many millions of years converted into phosphate minerals.

The Effect of Land Use

Human influence on the C, N, P and S cycles of terrestrial ecosystems has been felt in most parts of the world, for natural forests, semi-deserts and grasslands of the temperate regions have long been disruptively exploited for food and fiber. During the last few centuries about 10 per cent of the land surface, primarily forests and grasslands, has been transformed into agricultural land. The increased intensity of land use takes other forms as well, such as urbanization, but almost all have the long-term consequence of decreasing the reserves of C, N, P and S in soils.

For example during the 50-100 years of continuous cultivation in the Great Plains of North America, approximately 50% of the C and N, 30-40% of the S, and 10-30% of the P in the soil has been lost (Stewart, Cole and Maynard, in Bolin and Cook, 1983). A portion of the C, N, and S, and most of the P, is lost to harvest and erosion, but a larger fraction of the C, N, and probably S, is lost to the atmosphere in gaseous form or to aquatic ecosystems in dissolved or suspended form.

Figure 6: The global phosphorus cycle according to Richey (in Bolin and Cook, 1983). Reservoir sizes and annual fluxes are in 10^{12} g P.

Losses of C, N, and S occur because decomposition rates are increased in cultivated soils, due to their physical alteration and because less organic material is returned to the soil than in natural systems. When the addition of organic C to the soil declines, microbes are less able to immobilize the N and S released during decomposition. For at least part of the year, this may exceed the amount that plants can take up. These losses, after even one year of cultivation, reduce the ability of the soil to supply adequate amounts of N, P and S to crops, and fertilization is necessary to maintain high levels of production. Cultivated ecosystems can be managed so that loss of soil fertility is minimized and even so that organic matter, nutrient content, and productivity of once degraded sites are increased. However, these practices must now be relatively energy-intensive if they are to be effective on a time scale of decades.

The Effect of Burning Vegetation

The increase in the amount of organic material consumed as a consequence of human activities is substantial. According to one estimate, an average of about 0.3% of the total area of tropical forest is expected to be converted to other uses during each of the next 20 years (Lanly and Clement, 1979; Lanly, 1983).

Burning of the biomass during deforestation and shifting cultivation and dry grass fires in the savannas produce many important trace gases such as CO , CH_4 , N_2O and NO_x (Crutzen et al., 1979). Emissions of particulate matter cause a large aerosol loading in the atmospheric boundary layer above the tropical savanna. The extent to which these aerosols may influence the heat balance of the atmospheric boundary layer is not known. Savanna and forest fires have certainly occurred for hundreds or thousands of years, but it is not yet certain if the amount of material consumed has increased in recent years or if this burning has caused a change in the net flux of C, N, and S from terrestrial ecosystems.

Pollution of Rivers and the Ocean

The use of fertilizers, detergents and industrial chemicals containing N and P has increased dramatically in the past few

decades, and through waste disposal and runoff the transport of these elements in rivers has doubled over the past 30 years (Wollast, in Bolin and Cook, 1983). The introduction of these nutrients into marine coastal waters has resulted in an increased biological activity and a disruption of fragile food chains. In areas not subject to extensive mixing with and dilution by the open ocean, the entry of large amounts of P relative to N and Si have led to domination of communities by blue-green and brown algae, replacing the silica-containing diatoms that form the basis of many valuable food chains. Our understanding of coastal ecosystems is, however, inadequate to assess the effect of these and other man-made changes on the waters and ocean floor along the shore.

Man's effect on the global ocean system is still small. Measurements over the past three decades of the pressure of CO₂ in equilibrium with mid-latitude North Atlantic Ocean waters suggest an increase of 0.5 per cent each year (Takahashi *et al.*, 1983). Even though pollution of the ocean surface layer can be detected all over the world, the direct impact of man on the N, P, and S cycles has not been established by direct measurement in the open sea. For example, in the unlikely event that 20% of all P used by man were to reach and be used in the open sea, photosynthesis would increase by only 1-2 per cent. Due to the size of the oceans, cumulative effects take place only gradually. It is, however, important to monitor oceans carefully, because small changes in concentrations correspond to the transport of enormous amounts of material, which may be of importance for global geochemical budgets.

Summary

We are steadily increasing the use of the natural resources of the world. Clearly, this increase must not go beyond the level at which the global ecosystem will be irreversibly damaged, for the capacity of our planet to maintain life must not be diminished. The hypothesis has been advanced that the biosphere developed in such a manner that close to optimum conditions for life on earth prevail and are being maintained by the life processes themselves, despite man's intervention

(see Lovelock 1979). Regardless of the extent to which this might be the case, the biogeochemical cycles are crucial for maintenance of life on earth.

The consequence of burning hydrocarbons are apparent from the above discussion. So far, only a small percentage of the total recoverable fossil fuels have been used, and the C and S contents of untapped reserves are 50-100 times that which has been released to date. It is obviously crucial to assess what effects these future emissions will have on the natural ecosystem. Recent workshops held by the U.S. National Academy of Science (1983b) and NASA (1983) have focussed on methods needed to improve our understanding of the earth as a support system for life and to study anthropogenic change that might affect global habitability.

The ultimate impact of human intervention cannot be adequately deduced until the biogeochemical cycles are well understood. This will not be easy, for these cycles cannot be examined in isolation, but require the simultaneous attention of a diverse group of scientists. Furthermore, the study of global change must encompass a wider range of time scales and include larger areas of the earth than is currently being done. It is encouraging in this regard, that ICSU is now planning to establish an International Geosphere-Biosphere Program, for at present we are far from an integrated understanding of the global ecosystem.

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