Nitrogen, phosphorus and sulphur are essential elements in all living matter and are found in varying proportions to carbon, depending on the chemical nature of the compounds in which they occur. A pattern for the circulation of these elements in nature developed when microorganisms, plants and animals appeared on earth. The pattern was set by the physical and chemical environment, by the chemical nature of these elements, and by the geographic distribution of microorganisms, plants and animals. The appearance of *Homo sapiens* may not have had any great effect on these patterns as long as man was nomadic. That state of affairs changed when man formed settlements, where he transported vegetable matter and meat and where he deposited most of his wastes. The effect must have been particularly noticeable for phosphorus which is hardly leached from soils. Analyses of soil phosphate have, incidently, been used to locate archaeological settlements, (Arrhenius, 1931). Also in Eastern Canada, clumps of shumack trees are used by archaeologists as indicators of ancient Inchan campfires. These trees flourish on phosphorus enriched soils (R.E. Munn, pers. comm.). Hence a steady flow of phosphorus took place from nearby pastoral and agricultural areas, ending up in the soils of the settlements and their immediate surroundings. It is, of course, difficult to assess the impact of such a process on the environment; it is continuing today, with the difference that in some settlements a great deal of the accreted phosphorus is released into lakes and rivers. In some regions agriculture has been practised for a very long time which must have led to a sizeable depletion of phosphorus in soils, one reason for the present use of phosphorus fertilizers.

Similar processes must also have occurred for nitrogen and sulphur, although their chemistry would favour leaching from soils or return to the atmosphere. In semiarid areas, however, archeological sites sometime show accumulation of nitrate in and around former
sewage dumps – as observed, for example in prehistoric settlements in the Indus valley (K.G. Eriksson, pers. comm.). Such climatic conditions would also lead to high nitrate concentrations in ground waters formed in settlement areas. The high nitrate concentrations observed in ground waters in the semiarid parts of India and Africa are perhaps partly due to such human intervention in biogeochemical cycles in the past.

Man’s control of plants capable of fixing atmospheric nitrogen may constitute another source of interference in the nitrogen cycle. Such control may have been exercised even before the discovery of nitrogen fixing organisms via changing food habits, and, inadvertently, by the grazing of domestic herds in virgin areas.

Since one of the objectives of this report is to assess man’s impact on the biogeochemical cycles of nitrogen, phosphorus and sulphur, it is necessary to define a reference state for these cycles. In view of the foregoing discussion, this may not be so simple. If we go far back in time, we cannot unearth any quantitative information whatsoever on what a natural state may have been. Developments in natural sciences – except, perhaps, in astronomy – started sometime in the nineteenth century, more or less paralleling industrial development. The most obvious intervention by man in the cycles of nitrogen, phosphorus and sulphur also began at about the same time. It therefore seems necessary to refer to a preindustrial state rather than to a natural state. We can possibly assess the impact of man’s activity on these natural cycles during the last century as compared with the preindustrial state. To an inquisitive mind this is unsatisfactory. It is possible that some of the more recent impacts of man may have been amplified by “ancient” impacts, but this shall probably never be known.

A breakthrough in modern agriculture came with the invention of industrial processes for fixing atmospheric nitrogen. An almost unlimited reserve of nitrogen fertilizers is foreseen, although production may be limited by available energy. The fate of the fixed nitrogen has only recently been studied quantitatively. Denitrification returns nitrogen to the atmosphere as either molecular nitrogen or nitrous oxide. Atmospheric nitrous oxide seems to be involved in the destruction of ozone in the stratosphere. It is feared that an increase in the production of nitrous oxide in soils would affect the amount of ozone shielding the earth from solar ultraviolet radiation, which would otherwise kill all green plants on land. So this is a global problem. Locally and regionally, excess nitrate in water increases eutrophication in the same way as phosphorous. Nitrate concentrations in ground-water supplies may increase above safety levels.

The impact of man’s activity during the last century is spectacular in many respects. Through mining, phosphorus has become easily available, enriching food and waste. Through modern sewerage, a large part of this is conveyed into river courses, changing their ecology. Farming practices increase soil erosion, adding more phosphorus to streams. There is the concomitant threat of eutrophication of inland and coastal waters in some regions, plus the fear of depletion of mineable phosphate reserves, critical to world food supplies.

The growth of modern industry ushered in a demand for cheap energy, hitherto mostly supplied by fossil fuels. The latter contain sulphur, which, on combustion, is released into the atmosphere as sulphur dioxide and then deposited as sulphuric acid. The result is an accelerated rate of land denudation; regions with hard rocks and numerous lakes show ecological changes in the fresh-water systems. Sulphur emission also increase rates of corrosion and may become a health hazard in some areas.
Can problems such as those mentioned above be resolved by better knowledge of the biogeochemical cycles of nitrogen, phosphorus and sulphur? Looking ahead, it is difficult to see how we can improve our environment without first establishing fundamental facts. In addition, such facts will serve to offset the interminable speculation frequently passing for knowledge.

A useful way to assess existing knowledge is to estimate amounts of elements stored in various "reservoirs" or compartments in nature and fluxes of these elements between the different compartments. The division of nature into compartments is arbitrary to some extent. The number of compartments chosen for such a model of nature depends both on the geographical scale of the process under consideration and on the state of knowledge of the process. As seen from the flow charts presented in this volume, a fairly simple set of compartments is required for a global cycle.

The dynamic behavior of such models is, however, not discussed at all. This is a subject for future studies. Some comments on this subject may, nevertheless, be useful. In the past very simple approaches were often made implying a dynamic response of a compartment that was linear and of the first order, which means that the flux from the compartment is directly proportional to the storage alone. Under such circumstances the response is determined by one parameter, the turnover time, which is obtained by dividing the storage of a compartment by the steady-flux from it. However, most compartments in nature do not behave so simply. Taking organic matter in podsolic soils as an example, the turnover time is of the order of 100 years whereas the average age, based on carbon-14, is of the order of 1000 years. From this it is obvious that a major fraction of organic matter added to these soils is converted into carbon dioxide in a few year's time, while a small fraction becomes so resistant that it takes many centuries before it is converted to carbon dioxide; this fraction therefore constitutes the major fraction of organic matter in these soils. This is also true of the oceans and the atmosphere, respectively, taken as single compartments. The dynamic features of such compartments are properly described by distributions of transit times. The dynamic features must be taken into account for predictions of future states of biogeochemical cycles.

In the construction of flow charts, balancing of preindustrial fluxes is sometimes resorted to for computing some of the fluxes. This implies that flow charts represent means in stationary states, where limited fluctuations are permitted. Flux balancing is, however, questionable for compartments having large turnover times. Finally, fluxes obtained by balancing convey no new information.

Global flow charts integrate man's activity over the earth's surface. Since there are large regional differences in man's activity and the turn-over times of the substances in air is often small, the global flow charts do not give a fair picture of the impact of human activities, on the other hand, regional cycles are impossible to assess on the basis of present-day knowledge. Part of the cycles can in rare instances be outlined quantitatively — as will be seen when discussing the sulphur cycle. Such regional cycles will more clearly show the effect of man's activity.

From the compilations presented in this volume it is obvious that there are serious gaps in our knowledge of the biogeochemical cycles of nitrogen, phosphorus and sulphur. These gaps need to be bridged by research. Much of this research must of necessity be to obtain inventories, in particular on nitrogen, phosphorus and sulphur in soils,
since soils constitute a considerable storage. Such inventories will most likely reveal geographic patterns, which will aid our understanding of biogeochemical processes and their dependence on the physical and chemical environment. Such inventories should be included in the SCOPE project on biogeochemical cartography. Along with inventories, it is necessary to investigate the dynamics of various compartments, in particular the dynamics of soils, permitting forecasts of man's activities. It is necessary to consider both the rapid turnover within each compartment as well as the transfer rates between compartments.

In nitrogen and sulphur cycles, the atmosphere is a compartment on which knowledge is incomplete. Phosphorus is a minor component in the atmosphere, but concentrations and the origin of various phosphorus compounds are unknown. Patterns of deposition from the atmosphere are unknown over large areas. Much of this research requires rather extensive data collection on routine basis. There is also a strong need for development of better techniques for measuring air and precipitation concentrations of almost all compounds discussed. This is particularly so for measurements of background concentration values, i.e. those found outside cities and industrial regions and in the free atmosphere.

More specific research subjects of great urgency can be grouped according to elements.

**NITROGEN**

Denitrification is one of the most important processes in the cycling of nitrogen, but the denitrification rates in nature are poorly known. The influence of factors such as nitrate concentration, soil water content and oxygen concentration on both reaction rates and the $N_2O/N_2$ ratio of the gaseous end-products should be investigated both in terrestrial and aquatic habitats. The geographical distribution should be determined. It is important to verify if the soil can act as a sink for $N_2O$, and if this leads to a further reduction to nitrogen gas or if the nitrogen is assimilated by the soil microorganisms. A possible tropospheric sink for $N_2O$ should also be looked for. A better knowledge of the atmospheric $N_2O$ cycle is needed to improve the forecast for future $N_2O$ concentration levels. This is particularly important in view of the possible influence on the ozone layer.

The rates of biological nitrogen fixation in non-tropical waters are poorly known. The possible environmental effects of increased biological nitrogen fixation should be evaluated: an increase both with regard to symbiotic and non-symbiotic systems is probable. The possibility of genetical transfer of nitrogen fixing ability to non-fixing species and the resultant effect on the local and regional nitrogen cycles should be assessed. In order to diminish the increased use of nitrogen fertilizers, all aspects of biological nitrogen fixation should be investigated in order to find suitable species and systems for efficient use with present or new management techniques. The possible effect of pollutants (heavy metals, pesticides, etc.) on nitrogen fixation and other parts of the nitrogen cycle has already been investigated in some detail; a complete overview on the effect on the nitrogen cycle is, however, needed.

Man is manipulating the natural nitrogen cycle through various management prac-
tices, including the use of nitrification inhibitors, and methods should be sought to minimize any adverse effects, e.g. leaching of nitrate from soils, or decrease in biological nitrogen fixation. This is especially important, as the prices of nitrogen fertilizers will keep increasing, mainly as a consequence of the energy demanding production process.

The nitrogen flows are very variable on a regional scale, especially with regard to ammonium. Local and regional nitrogen budgets of $\text{NO}_x/\text{NO}_3$ and $\text{NH}_3/\text{NH}_4$ should be made in order to better elucidate man’s impact. The effect of a change in land use, including urbanization, on the nitrogen cycle should be evaluated.

If $\text{NO}_x$ is produced in gaseous form from soils, as well as from combustion processes, this might be an important component to account for the observed $\text{NO}_x$ concentrations in the atmosphere, and this should be further investigated. Further measurements on background levels of $\text{NO}_x$ and of $\text{NH}_3$, in the atmosphere are needed.

**PHOSPHORUS**

The concentration of phosphorus and the origin of phosphorus compounds in the atmosphere are unknown and should be investigated. For the study of the formation of ocean sediments, information about aeolian transport of phosphorus containing dust from land to ocean would be very valuable.

In order to be able to minimize the use of phosphorus fertilizers, the efficiency of various forms should be evaluated, also taking into account the effect of various types of fertilizers on the plant roots. Much information is, however, already available concerning the use of fertilizers.

Much of the phosphorus loadings of waters leading to eutrophication does not originate from the use of fertilizers but from industrial and household consumption. Means by which such uses of phosphorus could be eliminated should be investigated. Studies on the use of phosphorus from sewage sludge should be continued. The effect of various forms of sewage treatments (disposal on land or to waters or burning) on the distribution of phosphorus, as well as nitrogen and sulphur, should be investigated.

**SULPHUR**

The effect of acid precipitation on primary production should be assessed, both on a functional level and as an effect on the ecosystem level. The possibilities for drastic changes in i.e. leaf/needle pH and the resultant effect on photosynthesis and phyllosphere organisms should be studied.

In order to be able to estimate the total inventory of atmospheric sulphur, as well as its deposition on the ground, more detailed measurements are needed on the concentrations of $\text{SO}_2$ and sulphate aerosols, particularly in surface air in remote areas over the continents, as well as in higher layers of the atmosphere (particularly in the 5–10 km region) at a few different latitudes. Measurements of wet deposition of sulphate, particularly in remote areas, are recommended, provided that the problem of contamination can be handled properly. Furthermore, measurements of the sulphate concentra-
tion in cloud droplets in different regions of the world are recommended.

The basic chemistry of sulphur compounds in an atmospheric environment also needs to be better understood.

It is possible that the present sulphur deposition from the atmosphere in industrial areas with intensive agriculture is sustaining the crop yields, and that a reduction in atmospheric sulphur fall-out would affect the production from some crop lands. This should be investigated by making local sulphur budgets. The possibility of foliar SO2 absorption should be taken into account in this context.

An important part of the sulphur cycle is the production of reduced, volatile sulphur compounds (hydrogen sulphide and dimethyl sulphides), but the amounts thus released from decomposing organic matter is not known. The most important areas for this production may be intertidal flats. In situ measurements from such areas are urgently needed. Measurements are also recommended of air and precipitation concentrations of the various sulphur compounds in coastal areas and at different distances from the coast, in an area with tidal flats and where the anthropogenic contribution is either small or known.

Better data on sulphur in river runoff are needed, especially as sulphur is not included in the Unesco inventory on world river discharges into the oceans.

REFERENCES