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Global Environmental Change: the Causes and Consequences of Disruption to Biogeochemical Cycles

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Since the Earth first came into existence environmental change has involved the redistribution of elements and compounds via biogeochemical cycles. Such cycles link the lithosphere, biosphere and atmosphere within reciprocal relationships. These relationships have been profoundly altered by human activity but remain reciprocal. Examples are given to illustrate the magnitude of anthropogenic perturbations to the global biogeochemical cycles of carbon, nitrogen and sulphur. The major issues concern fossil fuel consumption which influences all three cycles, and agriculture which affects the carbon and nitrogen cycles in particular. Anthropogenic perturbations of these cycles has given rise to some of the most important environmental issues of the 1990s, notably global climatic change, acidification and cultural eutrophication. Policies and protocols to mitigate these problems indirectly represent efforts to manage biogeochemical cycles. In view of a likely 46 per cent increase in human population in the next three decades, biogeochemical perturbations will undoubtedly intensify, the impact of which will require increasingly close management. This will need to take into account the interactions between the cycles.

KEY WORDS: Carbon cycle, nitrogen cycle, sulphur cycle, global change, climatic change, environmental management.

THAT GLOBAL ENVIRONMENTAL CHANGE has been occurring since the Earth came into existence some 5000 million years ago is undisputed. This has resulted in a continual redistribution of chemical elements between the lithosphere and atmosphere. In the spirit of the Gaia hypothesis (Lovelock, 1972) it is acknowledged that life, as part of the biosphere, has played a crucial role in this redistribution; there is growing evidence, for example, that the earliest life forms arose soon after the formation of the Earth and thus became integrated into biogeochemical cycling at an early stage. Despite the astronomical forcing of major and minor climatic changes and lithospheric changes which have occurred throughout geological time, life and biogeochemical cycling have continued to operate and to contribute via feedback mechanisms to the regulation of global climate. Whilst it is a matter for debate as to whether or not this is a form of environmental determinism, i.e. neodeterminism (Mannion, 1994), it is a matter of fact that life and environment enjoy a reciprocal relationship.

There is no reason to doubt that this reciprocation will continue in the long term. There is equally no doubt that human-induced environmental change is now more dominant than naturally-induced environmental change and the rates of change occurring in the last *c.* 250 years are so much more rapid, that environmental systems may be unable to adjust to a new equilibrium (see Turner, 1997: 133). Even the rate of human-induced transformation is now much greater than in the pre-1700 period; much of this is the result of accelerated population growth and an enhanced material culture as standards of living have advanced.

This human transformation is manifest as perturbations in biogeochemical cycles; many forms of pollution, for example, are caused by the accumulation or excess of chemical species in situations where they become hazardous. Most local and global environmental issues relate directly to perturbations of biogeochemical cycles. Indeed, society has generally been unaware of its influence on these cycles until the concentrations have accumulated sufficiently so that some form of environmental degradation or impairment of environmental quality occurs i.e. where ecological/environmental thresholds have been crossed. Reinforcing factors may also come into

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operation, having been triggered by changes in the initial forcing factor. Some examples are given to illustrate these processes, which are usually underpinned by social, economic and/or political decisions/policies. Such decisions are rarely taken to bring about environmental change, but they often initiate a chain or cascade reaction, resulting in the crossing of ecological/environmental thresholds. Thus the identification of thresholds is a key aspect of environmental management. In the absence of monitoring programmes, thresholds are rarely recognized; usually the system becomes degraded before change becomes obvious. Only then is remedial action undertaken; in some situations the threshold can be recrossed through management, as illustrated below in relation to acidification. The impact of anthropogenic perturbations on biogeochemical cycles thus becomes the driving force behind management policy formation. However, in the case of biodiversity loss and especially species extinction, there is no redress.

Past and current trends in environmental change, i.e. human transformation of the Earth, are examined in terms of their impact on biogeochemical cycles at scales from the local to the global. Reference is also made to the underpinning driving forces such as population increase, migration, colonialism, etc. On the basis of available evidence for past and current patterns of environmental change and in the light of population growth rates and social trends, prospects for global environmental change in the next 30 years or so are examined. In addition the likely policy implications are outlined.

Past trends

Precisely when humans began to exert an appreciable impact on biogeochemical cycles is debatable. Certainly, it was many millennia ago. Indeed, there are at least two landmark events in the history of humanity which reflect its ability to influence biogeochemical cycles profoundly. The earliest of these is the use of fire to manipulate food resources, especially animal herds. This capacity is evident from the palaeoenvironmental/archaeological record and dates back one million years at least. Essentially, the firing of vegetation speeds up biogeochemical cycling by releasing nutrients from the biomass. These in turn stimulate new growth. This same mechanism underpins slash-and-burn agriculture and the management of many semi-natural ecosystems today. Whilst the initial use of fire was a landmark in human history, it was insignificant globally. The same is probably true of the inception of agriculture *c.* 10 000 years ago. It was monumental in terms of human development but affected only small areas initially. Of necessity, the clearance of natural vegetation, often by firing, for arable agriculture alters biogeochemical cycles through its impact on species composition and total biomass.

However, the initiation of permanent agriculture and the use of fire represent the exertion of control by humans over Nature. This continued and intensified throughout prehistory and history as agriculture spread. This has been fuelled by, and fuelled, population growth to the present levels of 5.3×10^9. Similarly, technological development has become another powerful agent of environmental change. Although this was a relatively late development in human history, having begun in the 1750s, it has had a profound effect on global biogeochemical cycles. In this context, the present interglacial period, which began *c.* 12 000 years ago is unique; agriculture and, later, industry have caused such substantial redistribution of many elements that globally and regionally significant pollution problems have resulted.

There are few unequivocal data on past biogeochemical trends. Moreover, hindcasts are fraught with difficulties and margins of error are often so great that resulting data are limited. However, recent concerns about climatic change caused by the accumulation of carbon dioxide and methane in the atmosphere have prompted research programmes to investigate the pools and fluxes involved in the carbon cycle, a diagrammatic representation of which is given in Figure 1. As a generalized model of the global carbon cycle, this along with models of other biogeochemical cycles, must be viewed with caution. For example, it is not known with certainty where all of the anthropogenically-produced carbon dioxide eventually becomes incarcerated as not all of it remains in the atmosphere (see discussion in Houghton *et al.,* 1996). Nor is it clear how much carbon becomes buried as carbonate in ocean sediments. This relates to the role of the oceans as a buffer or negative feedback in the global carbon cycle. However, additional information on past trends in the global carbon cycle, and particularly on the atmospheric component, has been determined from archives such as ice cores and ocean sediments. Other efforts have focused on the modelling of past and present fluxes to predict future trends. The longest record of changes in atmospheric carbon dioxide concentrations derives from the geological record. For example, Berner (1994) has reconstructed levels for various times in Earth history from several sources and has shown that low concentrations of carbon dioxide are associated with 'ice house' as opposed to 'greenhouse' worlds (see also the review in Mannion, 1997a).

The establishment of the ice ages of the Quaternary period, last *c.* 2×10^6 years, also marked a shift to oscillating atmospheric carbon dioxide concentrations: in the 'ice house worlds' of major ice advances low concentrations ensued whereas in the 'greenhouse worlds' of the interglacials high concentrations obtained. Analyses of air bubbles encapsulated in Arctic and Antarctic ice during the last

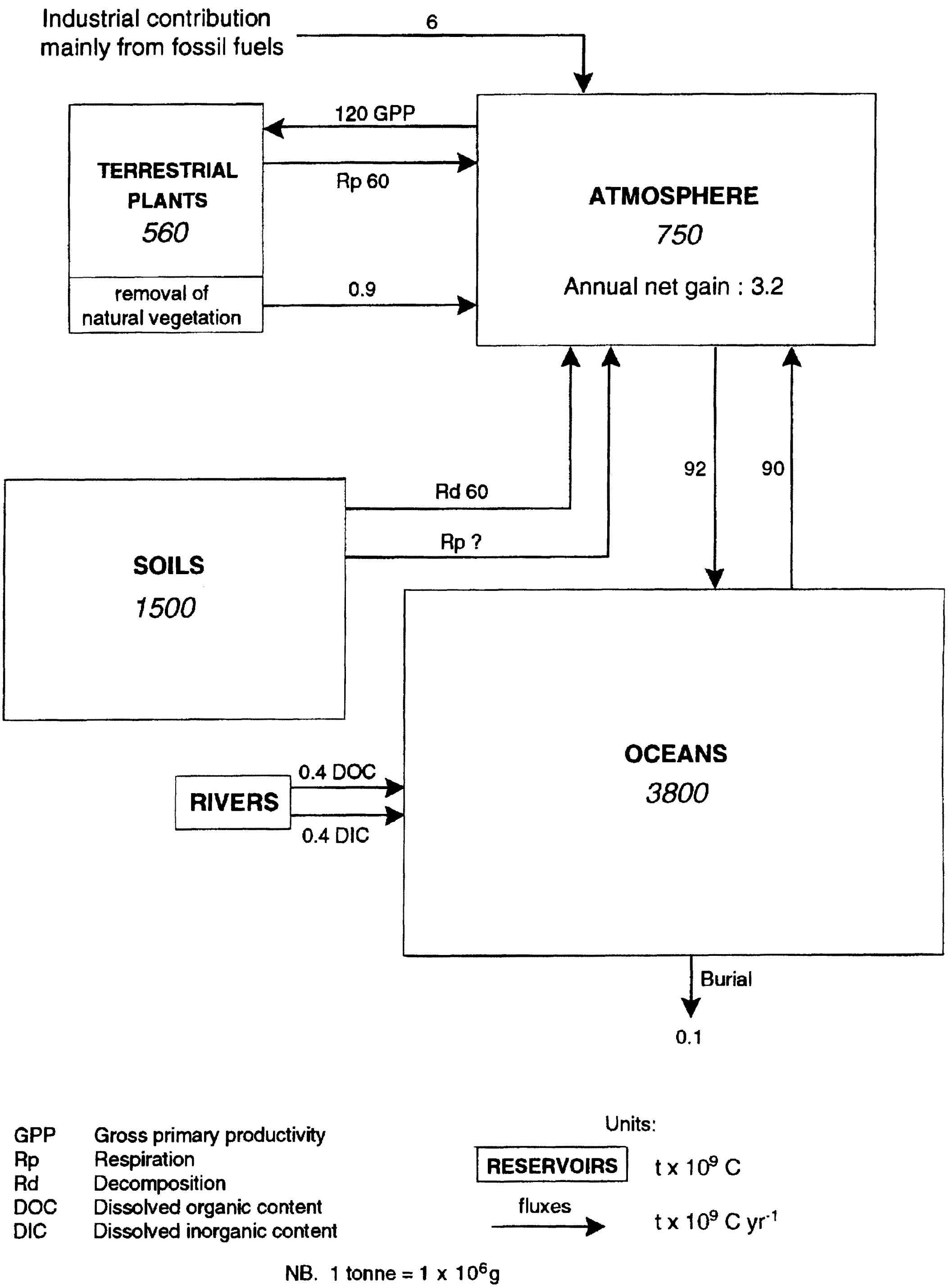

Fig. 1. The major reservoirs and fluxes in the global biogeochemical cycle of carbon. Data are from Schimel (1995) and Schlesinger (1997)

160 000 years, the last glacial global/interglacial cycle, provide a unique record of changes in atmospheric carbon dioxide concentrations (e.g. Johnsen *et al.*, 1992). Data from these polar cores reveal that during the last ice age atmospheric carbon dioxide concentrations were *c.* 190–200 ppmv and that they increased rapidly to *c.* 270 ppmv as ice sheets waned. This indicates the existence of a close relationship between atmospheric carbon dioxide concentrations and climatic change, though quite how this relationship operates is open to question. The dating of such changes also indicates that this relationship is dynamic; the transition from 'ice house' to 'greenhouse' can occur in just 2000 years (see reviews in Lowe and Walker, 1997 and Mannion, 1997b).

In addition, carbon dioxide data from ice cores reflect the substantial changes that have occurred since the beginning of the Industrial Revolution *c.*1750 (Houghton *et al.,* 1996). Additional detail derives from Antarctic snow, for which Battle *et al.* (1996) have obtained carbon dioxide concentrations for the last 100 years, and from monitoring data collected at the Mauna Loa observatory in Hawaii since 1958 (e.g. Keeling *et al.*, 1996). A summary is given in Figure 2 which shows that by 1800 carbon dioxide concentrations were beginning to increase markedly. By 1953 concentrations had increased to *c.* 312 ppmv from a pre-industrial value of *c.* 270 ppmv; by 1994 the concentration was 358 ppmv. The data for recent decades indicate an average annual rate of increase of *c.* 1.5 ppmv or 0.4 per cent (Houghton *et al.*, 1996). Undoubtedly, this increase is the result of human activity, notably fossil-fuel use, though land-use change (see Adger and Subak, 1996), especially that involving deforestation, and cement production are contributory factors. Indeed, the early rise in atmospheric carbon dioxide concentrations *c.* 1780–1850 was probably caused by increased deforestation, much of which was associated with the 'expansion of Europe' into the New World, Africa and Australasia. The impact of fossil-fuel consumption became particularly significant in the late 1800s (Houghton, 1994) and has since continued to accelerate. It is estimated that of the total anthropogenic emissions of carbon of $7.1 \pm 1.1 \times 10^9$ t/year (data calculated for 1980–1989), $1.6 \pm 1.0 \times 10^9$ t/year (i.e. *c.* 22.5 %) derive from land-use changes in the tropics, notably deforestation. Likely future emissions and their causes are discussed below.

An additional component of the carbon biogeochemical cycle is methane, the flux of which to the atmosphere has been altered by human activity. Although the concentration of methane in the atmosphere is much lower than that of carbon dioxide, changes in its concentration are important because methane is a more effective heat-trapping gas. Like carbon dioxide, it plays an important role in climatic regulation. Indeed, methane concentration data from ice cores mirror those of carbon dioxide (Jouzel *et al.*, 1993; Raynaud *et al.*, 1993) with high concentrations during warm periods and low concentrations in cold periods. Figure 2 shows the changes in atmospheric concentration of methane that have occurred in the last millennium. Levels of methane began to increase in the sixteenth century. According to Subak (1994) this was probably the result of an increase in populations of animals, biomass burning and irrigation in the Far East for rice cultivation. A rapid increase in atmospheric methane concentration began in the late 1800s, representing an increase from *c.* 800 ppbv to 1650 ppbv with a continued rate of increase of *c.*one per cent annually (Watson, 1992). This is attributed to the extraction and use of natural gas, increased paddy rice production, animal wastes, biomass burning, enteric fermentation, landfills and sewage treatment. Anthropogenic methane emissions to the atmosphere comprise 37×10^6 t/year (Houghton *et al.*, 1996).

The global nitrogen biogeochemical cycle (Fig. 3) has also been altered significantly by human activity, though there are few data available on past trends. Industry and agriculture have been, and continue to be, the major agents of change. Measurements of nitrous oxide concentrations, for example in the air bubbles of ice cores, indicate that in pre-industrial times atmospheric concentrations were *c.* 275 ppbv (Raynaud *et al.*, 1993). In 1994, the atmospheric concentration of nitrous oxide was 312 ppbv (Houghton *et al.*, 1996). This increase (Fig. 2) is attributed to fossil fuel use, biomass burning and nitrate fertilizer use.

Whilst nitrous oxide contributes to the enhanced greenhouse effect and is thus of global significance it also contributes to acidification which is of regional significance. These perturbations to the nitrogen biogeochemical cycle are thus causing substantial environmental change, the impact and implication of which have been widely reviewed (e.g. Watson *et al.*, 1996; Moore *et al.*, 1996; Mannion, 1997b). The use of nitrate fertilizer has resulted in environmental change of a different, but equally significant, kind involving the cultural eutrophication of freshwater, marine and groundwater environments.

This is a product of the past 80 years rather than the 250–300 years since the onset of industrialization on a large scale. Prior to *c.* 1920 nitrogen was cycled and recycled in agricultural systems via manuring, mulching and the inclusion of leguminous crop species in rotations. This changed with the commercialization of the Haber-Bosch process in 1913. Using heat and pressure, generated from fossil fuels, this process facilitates large-scale artificial nitrate fertilizer production. Today it consumes some one to three per cent of world energy production (Gilland, 1993), thereby contributing to the generation of greenhouse gases (see above) and transports *c.* 9.5×10^6 t/year of nitrogen (Jordan and Weller,

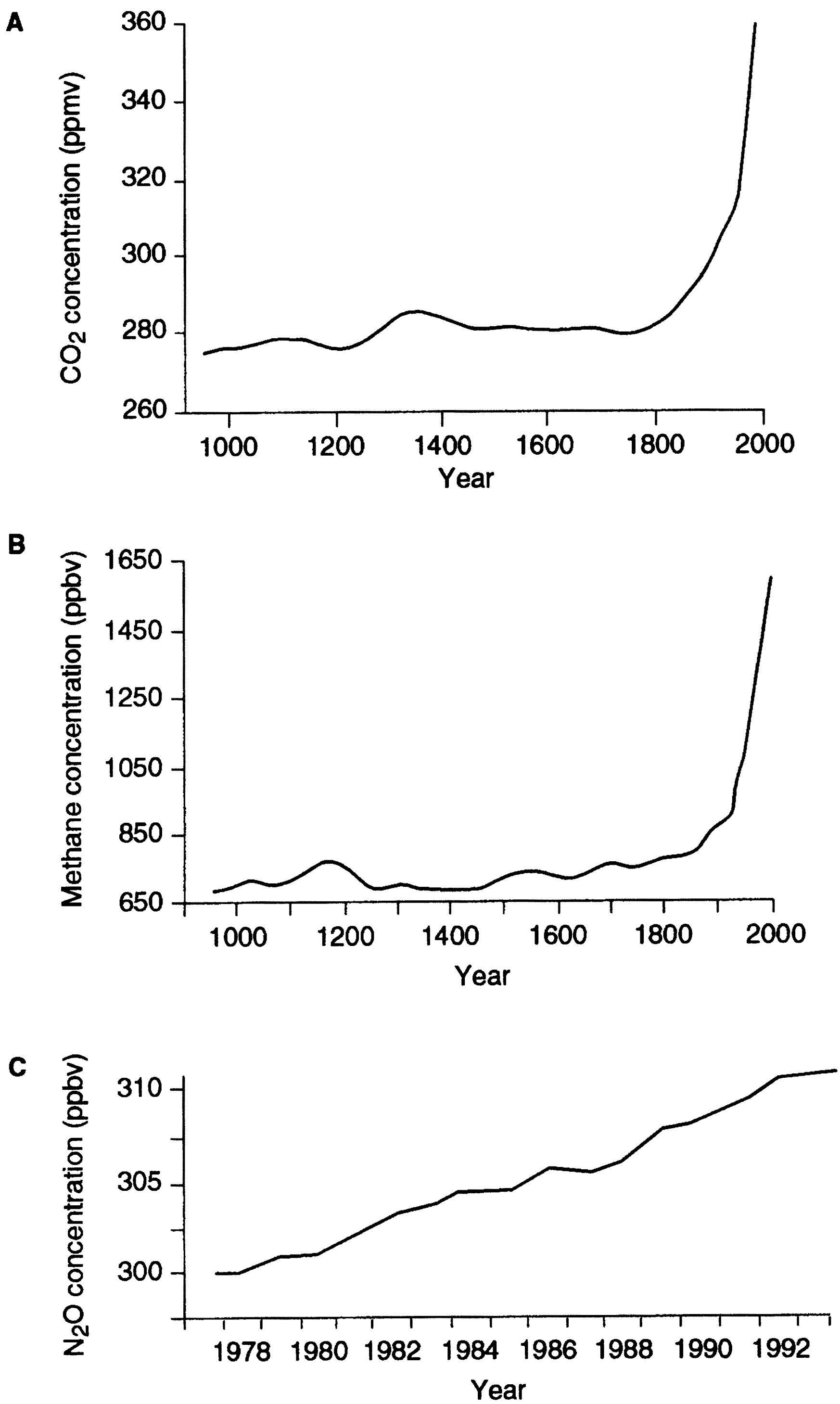

*Fig. 2. Changes in the atmospheric concentrations of **A** carbon dioxide (CO_2), **B** methane (CH_4) and **C** nitrous oxide (N_2O)*
Source: Houghton *et al.*, 1996

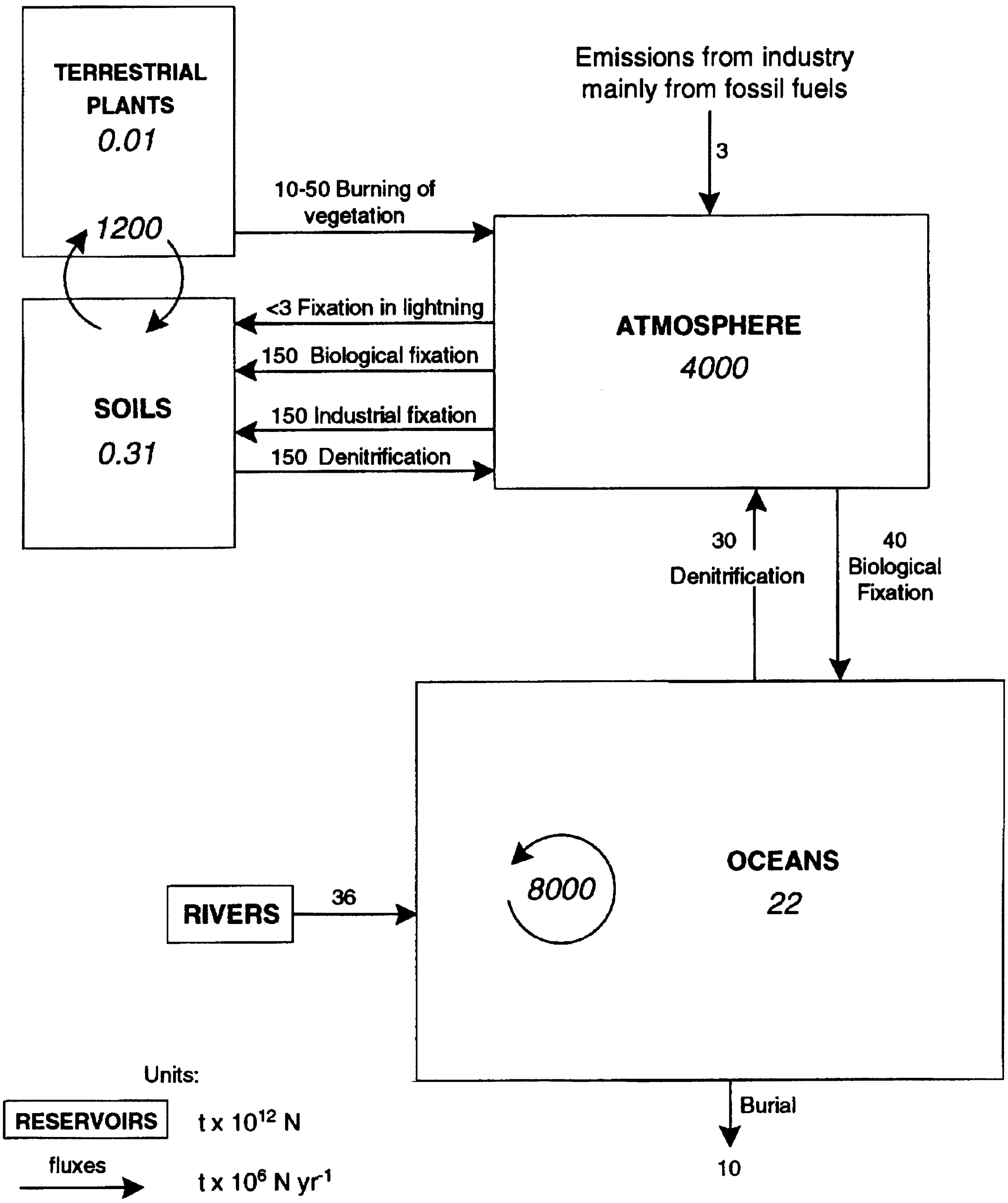

Fig. 3. The major reservoirs and fluxes in the global biogeochemical cycle of nitrogen. Data are from Jaffe (1992) and Schlesinger (1997)

1996) from the atmosphere to the biosphere. According to Galloway *et al.* (1995), the Haber-Bosch process alone accounts for *c.* 57 per cent of anthropogenic nitrogen fixation (Fig. 3) as compared with the *c.* 14 per cent derived from fossil fuels, with an additional *c.* 29 per cent deriving from the cultivation of legumes. Much of the nitrogen (as nitrate etc.) is not used by crop plants and eventually enters aquatic systems causing nutrient enrichment and aquatic food chain disruption (see reviews in Mannion, 1995; 1997b). This problem, which is particularly apparent in the developed world where 'industrialized' agriculture is prevalent, has implications not only for ecosystem structure and function but also for tourism and leisure industries and human health. Moreover, cultural eutrophication is spreading rapidly in developing countries as they increase their use of artificial fertilizer.

The characteristics of the global biogeochemical cycle of sulphur have been examined by Andreae

(1991) and Charlson *et al.* (1992); the essential pools and flux rates are shown in Figure 4. The major anthropogenic perturbation of this cycle is fossil-fuel combustion which releases $70–80 \times 10^6$ t of sulphur annually from the lithosphere into the atmosphere. Most returns to the biosphere as sulphurous and sulphuric acids which cause ecosystem acidification along with nitric acid derived from the anthropogenic perturbation of the nitrogen cycle (see above, Fig. 3 and review in Mannion, 1997b). Acidification reduces biodiversity, impairs water quality and erodes buildings. As with carbon and nitrogen there is evidence from polar ice cores for changes in sulphurous emissions. For example, Mayewski *et al.* (1990) have shown from a Greenland ice core that since 1750, sulphur dioxide emissions have increased from *c.* 8×10^6 t/year to *c.* 30×10^6 t/year with the greatest increase occurring between *c.* 1900 and 1960 (see also Pham *et al.*, 1996). In addition, sulphurous emissions, both natural and anthropogenic, influence global climate (see review in Lovelock, 1997) by providing aerosols that facilitate cloud formation. This contributes to maintaining Earth surface temperatures within a limited range by its cooling effect i.e. clouds reflect sunlight, preventing it reaching the Earth's surface, and they radiate heat which cools the atmosphere. Consequently, one pollution type – the sulphurous aerosols – is counteracting the impact of another pollutant – carbon dioxide (see reviews in Charlson *et al.*, 1995).

There are other biogeochemical fluxes which have been altered by direct or inadvertent human activity e.g. the phosphorus and lead biogeochemical cycles have been affected by mining: phosphates for fertilizers and lead for a range of industrial processes and products including an anti-knock additive in petrol. All of these perturbations have given rise to pollution problems. Excess phosphate entering aquatic en-

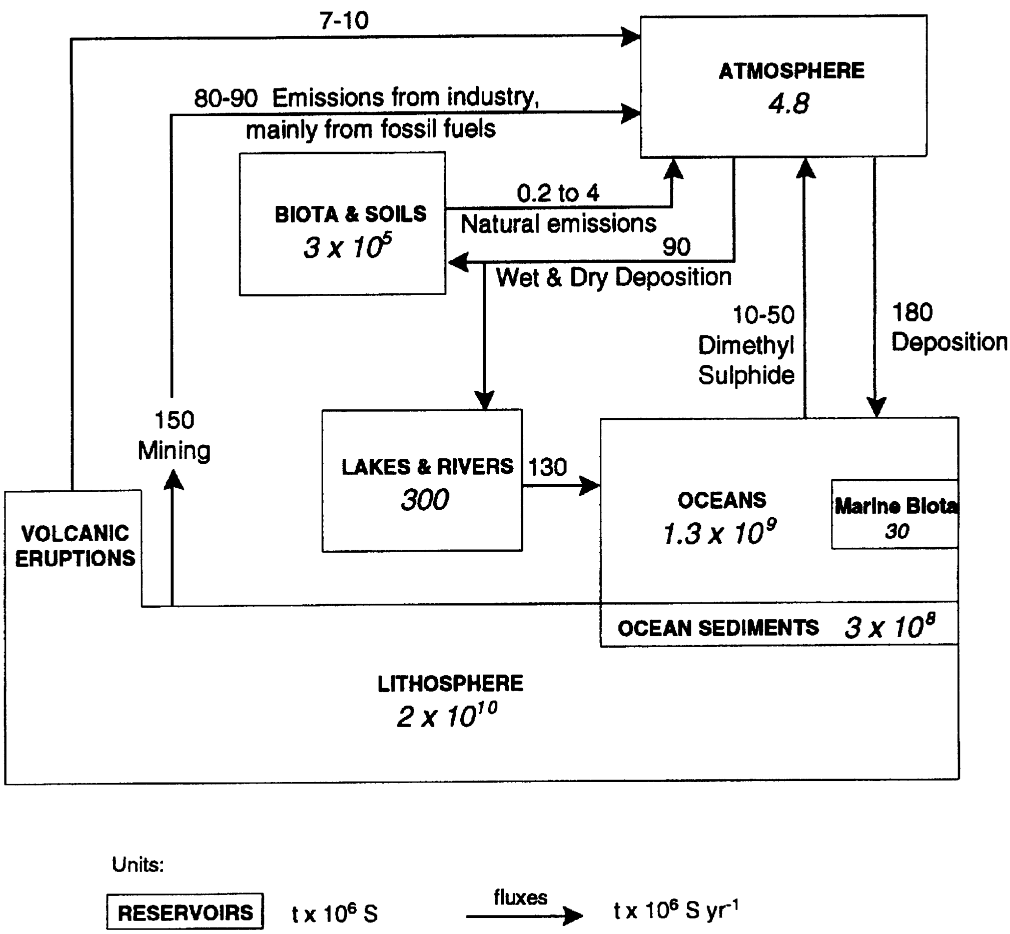

Fig. 4. The major reservoirs and fluxes in the global biogeochemical cycle of sulphur. Data are from Charlson et al. *(1992) and Schlesinger (1997)*

vironments contributes to cultural eutrophication while excess lead can be a human health risk. These problems, like those discussed above, have been generated by either agriculture or industry. As an organism, *Homo sapiens sapiens* is altering the chemical environment in which it lives with concomitant repercussions for life on Earth in the spirit of Gaia. Whether there will be worse repercussions for *H. sapiens sapiens* itself remains to be seen.

Present and future trends

All indications are that perturbations to global biogeochemical cycles will continue well into the next millennium. Population increase in particular is a fundamental driving force. Whilst the relationship between people and resource use is complex and spatially varied owing to material standards of living (this encompasses a complex set of variables which include income, aspirations in terms of wealth generation, and lifestyle), there are two irrefutable facts: humanity persists and reproduces as a result of resource manipulation and all resources derive from abiotic and biotic components of the Earth. A corollary of these principles is that all resource manipulation involves biogeochemical cycling at various spatial scales which gives rise to global environmental change. At a basic level all individuals are reliant on agriculture, itself a technology that manipulates biogeochemical cycles and energy flows (Mannion, 1995). Any population increase enhances the pressure on agricultural systems which must intensify, or expand, or both. Moreover, aspirations to improve material culture/standards of living are leading to increased industrialization. Overall, increased population and improved standards of living intensify perturbations to biogeochemical cycles and thus cause environmental change.

Real and projected population trends are shown in Table I. By 2025 world population is projected to grow from *c.* 5.8×10^9 now to *c.* 8.3×10^9 i.e. an increase of 43 per cent in just 28 years, representing an average annual increment of between 80×10^6 and 87×10^6. Spatially, population increase will not be uniform, as shown in Figure 5. For example, Shen (1998) estimates that by 2030 the population of China will have reached 1594.6 million, an increase of almost 23 per cent on the 1995 figure, despite measures, since the 1970s to control population growth. The highest rates of increase, as now, will be in developing countries. This projected increase in mouths to feed is likely to have serious ramifications for agriculture and thus for the biosphere in general. Equally important is the accelerating trend toward industrialization which is apparent in many developing countries, notably India, China and South East Asia. If increases in fossil-fuel consumption occur, as is likely, they will augment global warming and acidification. Such agricultural and industrial intensification will accentuate anthropogenic perturbations to the global biogeochemical cycles of carbon, nitrogen and sulphur though it is not possible to determine precisely the magnitude of these perturbations, or their impact. They can hardly be anything but considerable.

TABLE I

Recent and projected population concentrations

	Population in 1995	*Population in 2025*
Asia	3458.0×10^6	4960×10^6
Africa	728.1×10^6	1495.8×10^6
Europe	727.0×10^6	7118.2×10^6
Latin America and the Caribbean	482.0×10^6	709.8×10^6
North America	292.8×10^6	369.6×10^6
Oceania	28.5×10^6	41.0×10^6

Source: World Resources Institute, 1996

In relation to agriculture, for example, food production will have to increase rapidly and substantially to feed an additional 2.5×10^9 people. Moreover, the reliance of many developing countries on income derived from the export of agricultural products means that pressure on agricultural systems will intensify. Indeed FAO (1997) have estimated that an annual increase in world food production of 1.8 per cent annually will be necessary until *c.* 2010. This can be achieved either by increasing the productivity of existing agricultural land or by expanding agricultural systems into natural and semi-natural habitats. The case for increasing the productivity of existing agricultural systems has been presented by Avery (1995) who believes that this is the best way to ensure the preservation of the world's remaining natural ecosystems. He suggests that all the available aspects of 'industrialized' agriculture should be employed within a framework involving the strict regulation of the use of crop protection chemicals, fertilizers, biotechnology etc. Whilst this argument has some validity, it is somewhat naive because total containment is impossible; the impact of agricultural systems often occurs well beyond their boundaries e.g. the cultural eutrophication of aquatic environments referred to above. Moreover, the 'industrialization' of agriculture inevitably involves using fossil fuels which contributes to global warming.

Conversely, however, any expansion of agricultural systems will occur at the expense of natural and semi-natural ecosystems. One consequence of this is accelerated species extinction which may impair the capacity of ecosystems to provide feedbacks in biogeochemical cycles and represents the loss of potential resources. Research on the relationship between species diversity and primary productivity in ecosystems indicates a positive relationship between the two (Naeem *et al.*, 1994; Tilman *et al.*, 1996). Thus species extinction through ecosystem disturbance,

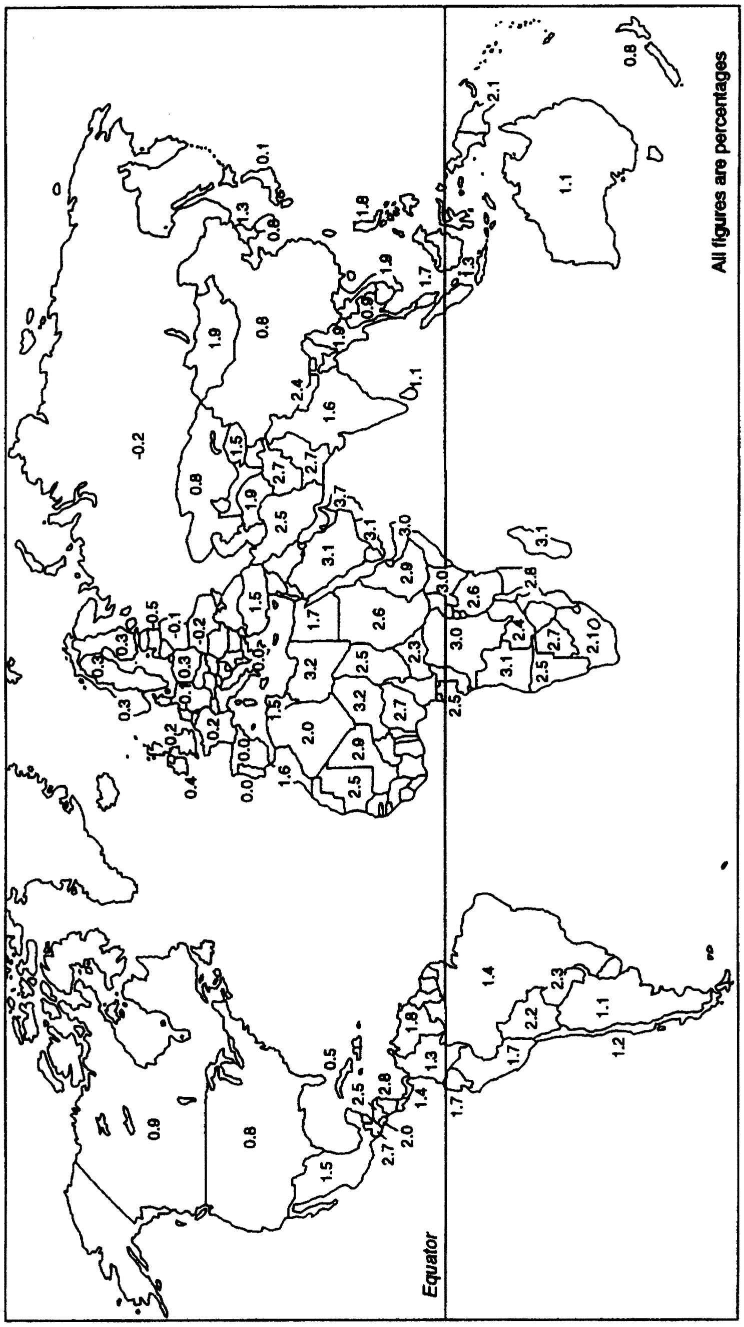

Fig. 5. Average annual rates of population change from 2000 to 2005. Based on World Resources Institute, 1996

fragmentation and pollution is detrimental to biogeochemical cycling. It may also mean the denial of opportunities for the future as the unique properties and capacities of species are lost. The removal of natural vegetation also results in a loss of stored carbon from the standing crop biomass and the organic content of the soil. Murdiyarso and Wasrin (1995) have calculated that 30×10^6 t of carbon are released to the atmosphere annually when 60×10^3 hectares of tropical forest in Sumatra, Indonesia, are converted to agricultural land. The imprecision of estimates concerned with global emissions of carbon are, however, reflected in the survey of Adger and Brown (1994). These estimates range from 400×10^6 to 2900×10^6 t for 1980. Moreover, Sedjo (1993) estimates that some 1700×10^6 t of carbon are produced annually from tropical deforestation alone, an estimate which is similar to the 1600×10^6 t suggested by Houghton (1995) and the IPCC (Houghton *et al.* 1996), as discussed above, and in the range 1200×10^6 to 2300×10^6 t quoted in Melillo *et al.* (1996).

In order to provide food for a population increase of *c.* 2×10^9 by 2025 in tropical regions, it is inevitable that further deforestation will ensue with yet further carbon emissions. Of the 1200×10^6 t of carbon currently sequestered in the world's forests, about 400×10^6 t are in tropical forests (Woodwell, 1993). How much of this will enter the atmosphere in the next two decades? Even allowing for additional carbon sequestration in boreal forests and plantations, which currently accounts for *c.* 700×10^6 t annually, the amount of carbon accumulating in the atmosphere as a result of tropical deforestation is likely to increase well beyond the current 900×10^6 t. Unless aggressive policies of forest conservation, tree planting and the intensification of agriculture on existing agricultural land are pursued, this figure will rise rapidly and will certainly be in excess of 1000×10^6 t by 2000. This will require policy decisions at local, regional and national levels. Again, the driving force is not the desire to manage biogeochemical cycles but to avert adverse impacts of their perturbation. The nature of the agriculture will also influence emissions, especially of methane. For example, increasing numbers of livestock and paddy rice cultivation will enhance methane production. According to an analysis of FAO data by Alexandratos (1995) the area under paddy rice will increase by two per cent by 2010, if production and yields also increase. In addition, Alexandratos predicts that in developing countries overall the demand for livestock products will increase by two per cent annually and that production in these countries will increase by 3.8 per cent by 2010. The highest increases will comprise four per cent in pig meat production, a 5.1 per cent increase in poultry production, a 3.1 per cent increase in sheep/goats and a 2.7 per cent increase in cattle production. Accordingly, and in view of increased clearance of natural vegetation communities that also enhance methane production, methane concentrations are clearly set to increase into the twenty-first century.

Continued increases in fossil-fuel consumption will also augment anthropogenic perturbations of the carbon and sulphur cycles. According to World Resources Institute (1996), world commercial energy consumption between 1973 and 1993 increased by *c.* 49 per cent. The increase was not globally uniform as illustrated in Figure 6 and Table II. Currently, emissions are increasing most rapidly in developing nations. The intensifying industrialization of China, India, Korea and Malaysia is the major cause. In China alone, coal production increased from 872×10^6 t in 1985 to 1080×10^6 t in 1990; despite this the importance of coal as a fuel decreased to 72 per cent of total used with the additional 28 per cent comprising increases in oil and natural gas consumption (Zhang *et al.*, 1995).

In relation to future perturbations to the carbon cycle, four emission scenarios have been suggested by Houghton *et al.* (1990) to estimate how much carbon dioxide will be present in the atmosphere between 2000 and 2100. If energy consumption patterns and rates of deforestation continue as at present i.e. the 'business as usual' scenario, atmospheric carbon dioxide concentrations will reach *c.* 800 ppm i.e. more than double present concentrations. This could generate an average increase in global temperatures of 2°C by *c.* 2050 or 2075. If, as an alternative, there is a massive switch from fossil fuel to nuclear fuel in the near future, atmospheric carbon dioxide concentrations may remain below 450 ppm by 2075. Even this represents an increase over the present concentration of 360 ppm and in view of the problems associated with nuclear power, it is unlikely to occur. For scenarios intermediate between these two extremes, involving a shift to natural gas from coal coupled with net global afforestation or a shift to nuclear and renewable power sources in the next 50 years, atmospheric carbon dioxide concentrations are predicted to rise to *c.* 550 ppm and *c.* 475 ppm respectively (Houghton, 1994). Consequently, from an average of *c.* 270 ppm in pre-industrial times, carbon dioxide concentrations may double in the next 50 to 100 years. A vast amount of carbon will have been fluxed from stores in the biosphere and lithosphere by human activity. It is inevitable that this perturbation to the cycle of an element which Nature has taken out of circulation and sequestered in various reservoirs will have consequences.

Increasing fossil fuel consumption will also lead to increased sulphurous (and nitrous gas) emissions giving rise to more widespread acidification than occurs at present. Currently the regions seriously affected by acidification are in the northern hemisphere where

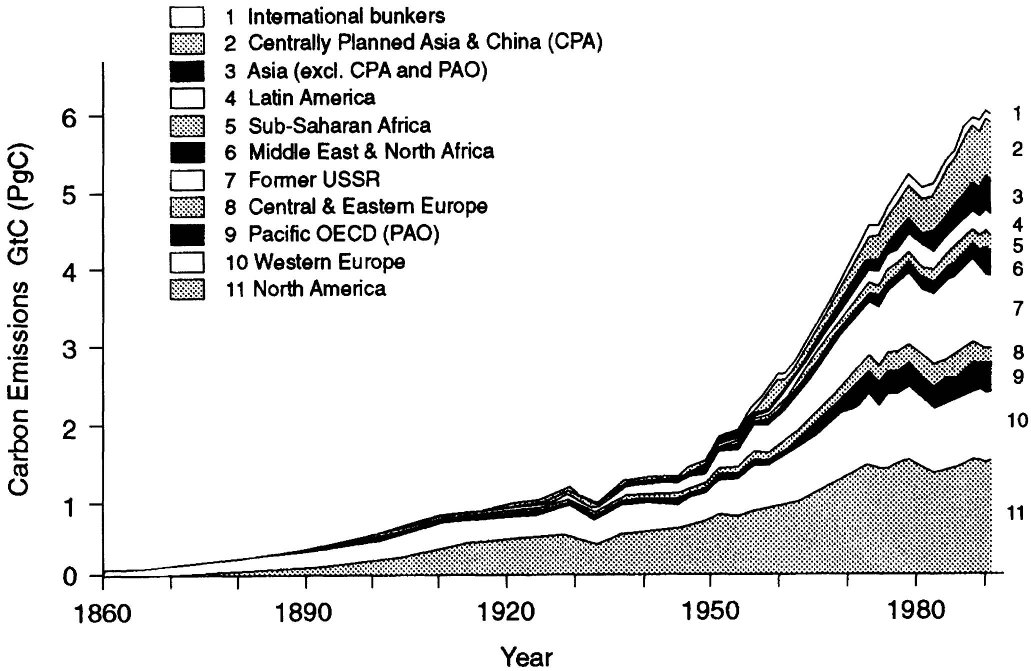

Fig. 6. Global energy-related CO_2 emissions by major world regions in Gt C/yr (Pg C/yr)
Source: Grübler *et al.*, 1996

areas of acid bedrock receive industrially-derived emissions of sulphurous and nitrous acids. However, acidification is becoming apparent in several newly-industrializing countries. For example, between 1980 and 1990 emissions of sulphur dioxide increased from *c.* 13.4×10^6 t to 20.0×10^6 t in China and from *c.* 2.0×10^6 t to 3.1×10^6 t in India (United Nations Environment Programme, 1993). The impact of these and other emissions in Asia has been reported by Foell *et al.* (1995) who draw attention to declining air quality, increasing acidic deposition and transnational pollution. The latter is particularly important for China's neighbours (e.g. Chung *et al.*, 1996) and most of China's cities have acid-damaged buildings and poor air quality (Byrne *et al.*, 1996). In terms of future energy consumption, Chan and Lee (1996) predict that by 2000 the energy consumption of China will have increased by 44 per cent on 1990 levels i.e. the country will require 1.42×10^9 t coal equivalent. Moreover, projections of world energy consumption discussed in World Resources Institute (1996) indicate increases ranging from 98 per cent to 30 per cent. Whilst not all of this will be fossil fuel there will still be a substantial output of sulphur. This will cause increased acidification, especially in South America and Asia.

Increasing fossil fuel consumption will also contribute to the enhanced perturbation of the nitrogen biogeochemical cycle through the release of nitrogen oxides. Additional nitrous oxide will contribute to greenhouse warming and to stratospheric ozone depletion, whilst nitrogen dioxide will contribute to acidification. However, additional anthropogenic perturbation to the nitrogen biogeochemical cycle

TABLE II

A *Energy consumption per continent and per capita*

	Total PJ 1993	*% change since 1973*	*Per capita GJ 1993*	*% change since 1973*
Africa	8805	144	13	41
Asia*	95 679	185	28	92
Latin America	16 300	*c.* 90	35	*c.* 30
Europe	108 523	*c.* 30	318	*c.* −3
Oceania	4595	93	166	44

* 31% derives solely from China

B *Energy consumption for selected countries*

	Total PJ 1993	*% change since 1973*	*Per capita GJ 1993*	*% change since 1973*
Burkina Faso	8	237	1	150
Nigeria	705	420	7	221
Germany	13 724	2	170	n/a
UK	9518	10	164	7
USA	81 751	13	317	−7
Ecuador	245	305	22	141
China	29679	179	25	110
India	9338	258	10	128

Source: World Resources Institute, 1996 will be caused by increases in artificial fertilizer use. Currently, the annual fixation of nitrogen from the atmosphere through the Haber-Bosch process is responsible for transporting 150×10^6 t of nitrogen from the atmosphere to the biosphere, an amount equal to that fixed biologically (Fig. 3). How much this is likely to increase in the future is dependent on the response of agriculture to human population increases. In turn, the response of agriculture will be determined to a large extent by national policy. Between 1983 and 1993 global use of fertilizer decreased from 88 Kg ha^{-1} to 83 Kg ha^{-1}, with the largest reduction in Europe and North America (World Resources Institute, 1996). In contrast, there was an increase from 84 Kg ha^{-1} to 118 Kg ha^{-1} in Asia and from *c.* 31 Kg ha^{-1} to 59 Kg ha^{-1} in Latin America. Since these are regions with the highest projected population growth into the twenty-first century it seems likely that their use of artificial fertilizers will increase substantially. Alexandratos (1995) suggests that during the next century fertilizer use will increase by *c.* 3.5 to 4.8 per cent in developing countries, with the most significant impact in North Africa/Near East and Asia. Although the predictions do not reach values as high as 170 Kg ha^{-1}, the average annual application in Europe today, these increases will inevitably cause widespread cultural eutrophication.

Policy implications

There are many policy implications of these trends. The first is the international control of greenhouse gas emissions and the establishment of protocols to reduce them. These are emotive and complex issues; the reliance of industrialized and industrializing countries on fossil fuels is so fundamental that altering the relationship between development and energy is a major task. Whilst many developed countries are beginning to reduce their fossil fuel consumption reflecting an 'energy transition' they are still heavily reliant on fossil fuels. For example, average annual per capita consumption of commercial energy in Europe is 148 GJ (1993 values quoted in World Resources Institute, 1996) and in North America it is 318 GJ. In contrast the values are 28GJ and 13GJ in Asia and Africa respectively. Moreover, the newly industrializing countries recognize the pivotal role of fossil fuels in their development and do not wish to, or feel they cannot, engage in emission reductions. This is illustrated by the absence of representatives of India and China at the second Earth Summit in New York, June 1997. It must also be pointed out that most developed countries have failed to meet reduction targets for greenhouse gas emissions. This highlights an interesting paradox: the problem of climatic change is recognized and acknowledged yet there is serial failure to curtail carbon emissions which are a major cause of that change. Indeed, the international climate convention, which was established at the first Earth Summit (i.e. the United Nations Conference on Environment) held in Rio de Janeiro in 1992, has not proved to be particularly effective in terms of tackling the underpinning causes of climatic change. This convention (see description in Maunder, 1994) was not, however, concerned directly with the management of the carbon cycle but with climatic change, including strategies to accommodate and adapt to that change.

Other aspects of energy policy include investment in technology to combat emissions. Such an approach tackles the symptoms rather than the underpinning causes; although this represents a short-term response it is essential in the face of such a serious problem. Examples of emission treatment to reduce carbon output have been discussed by Al-Khouli *et al.* (1996) and include increasing the efficiency of fossil-fuel conversion to gas and electricity and the decarbonization of fossil fuels. Other direct possibilities for reducing fuel consumption include:

1 appropriate building and settlement design;
2 fuel-efficient transport;
3 increasing reliance on efficient public transport systems; and
4 reducing fossil-fuel inputs to agriculture.

Indirect possibilities include the adoption of land-use practices that sequester high volumes of carbon e.g. afforestation, forest conservation and management. Such possibilities have been discussed in Watson *et al.* (1996).

In relation to the impact of disruption to the global sulphur cycle, some policy measures have been implemented since the early 1980s as a result of the *Geneva Convention* of 1979. This international convention produced the so-called '30 per cent club', the Helsinki protocol signed in 1985 by 20 European countries. Its aim was to reduce sulphur dioxide emissions by *c.* 30 per cent of 1980 levels by 1993. Another protocol was signed in Oslo in 1994 which included specific emission targets. These have been achieved mainly by the introduction of desulphurization i.e. the removal of sulphur dioxide from emissions before they are released into the environment, and a switch to sulphur-poor fuels such as natural gas. The decline in heavy industry in parts of the developed world has also contributed to declining sulphur dioxide emissions. There is evidence for the recovery of acidified environments in Scotland and Eastern Canada where lake pHs are beginning to increase (see review in Mannion, 1997b). In the next few years many developing industrializing countries will need to consider similar measures to curtail acidification, though such legislation is usually reactive rather than precautionary. Overall, however, little action has been taken to limit nitrous emissions from fossil fuel consumption, so environmental change caused by this perturbation to the nitrogen biogeochemical cycle remains uncontrolled.

Policies relating to fertilizer use, another means of altering the biogeochemical cycle of nitrogen, have been in operation in North America and Europe since the 1970s. In the USA, for example, legislation to restrict point-source effluent has improved water quality in many large lakes. However, non-point source pollution is much more difficult to control and this was specifically addressed in the *1987 Clean Water Act* which requires individual states to control water pollution through management. The concept of 'best management practices' underpins water quality control policies; they address watershed management in a holistic fashion, e.g. crop type, regulation of fertilizer application and erosion control etc. Where control measures have been in place, water quality has improved and the process of cultural eutrophication has been reversed. In the UK the *1989 Water Act* facilitated the establishment of 'nitrate sensitive areas' in which nitrate control could be required by law, with compensation given to farmers to encourage 'good practice', including the conversion of arable land to pasture. In the European context, EU legislation has identified 'vulnerable zones' in which land use could be altered by order to reduce nitrate in rivers and aquifers. In developing countries, however, there is less concern with environmental or water quality than with productivity, especially in the face of rapidly growing populations.

Conclusion

The anthropogenic perturbation of the global biogeochemical cycles of carbon, nitrogen and sulphur has been considerable. Such perturbations have contributed to widespread environmental change. Although manifest at local and regional levels, acidification and cultural eutrophication are components of global land and water transformation. They represent the local/regional over-abundance of sulphur and/or nitrogen caused by human activity. Similarly, the conversion of forests to agricultural land is local or regional but causes an enhanced flux of carbon to the atmosphere.

Truly global environmental change is, however, a product of anthropogenic perturbations to these cycles. The enhanced flux of carbon, sulphur and nitrogen to the atmosphere through fossil-fuel use is causing climatic change which will, in turn, influence biogeochemical exchanges further through its impact on lithospheric and biospheric processes.

The mitigation strategies, including legislation, do not simply involve climatic conventions, curtailment of acid emissions or nitrate leaching. In reality, they effectively contribute to the control of biogeochemical cycles at the local and/or regional scales. Inevitably such schemes will contribute to defining the characteristics of the pools and fluxes of biogeochemical cycles at the global scale. Moreover, it must be recognized that almost all human activities involve manipulation of biogeochemical cycles either directly or indirectly, and that many forms of pollution are the result. It must also be recognized that biogeochemical cycles do not operate in isolation but interact at all scales. Consequently, environmental management policies which indirectly influence one biogeochemical cycle may significantly influence others, with unforeseen consequences.

As world population continues to grow rapidly and changes in agriculture and industrial development ensue, anthropogenic disruption of global biogeochemical cycles will intensify. The magnitude of that disruption is difficult to establish because biogeochemical processes are imperfectly understood and because technological innovations may temper, or intensify, the disruption. However, a *c.* 46 per cent increase in human population in the next three decades will inevitably bring substantial biogeochemical change. The need for regulation at scales from the local to the global will increase in response. Will society rise to the challenge?

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