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THE GLOBAL PHOSPHORUS CYCLE

U. PIERROU

Department of Limnology, Box 557, University of Uppsala, S–751 22 Uppsala, Sweden

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ABSTRACT

In this article the global biogeochemical cycling of phosphorus is treated from a quantitative angle. Not only the various transfers but also the various inventories of phosphorus have been calculated from literature values. The atmospheric part of the phosphorus cycle is largely unknown. A total global deposition rate of 6.2–12.8 Tg P yr^{-1} was estimated.

The greatest flows are mediated by the biota in terrestrial and marine systems; the former with a rate of between 100 and 300 Tg P yr^{-1} and the latter with a magnitude of about 1000 Tg P yr^{-1}.

River discharge (17.4 Tg P yr^{-1}) and sedimental rate (13 Tg P yr^{-1}) were found to be about the same as the amount withdrawn from rocks by mining. The biogeochemical cycling of phosphorus is greatly affected by man, who thereby creates several environmental problems.

INTRODUCTION

The element phosphorus (Gr., = light-bearing) was synthesized in 1669 by the German merchant and alchemist Henning Brand, who called it "the cold fire". In 1771 phosphorus was discovered by C.W. Scheele and J.G. Gahn to be an important constituent of bone. Bone ash thus became, and remained for a long time, the major source of the element. This fact is shown by the concentration unit sometimes used for apatite rock, bone phosphate of lime, BPL (Emigh, 1972).

Phosphorus is vital to life and is non-substitutable in biological systems. It is a constituent of deoxyribonucleic acid, DNA, ribonucleic acid, RNA, the energy carrying molecule adenosine triphosphate, ATP, and its di- and monophpsphate precursors ADP and AMP. The DNA molecules of the chromosomes are adapted for storage, replication and – together with RNA – transcription of genetic information. The RNA molecules transcribe the genetic information, and also form templates at which proteins can be synthesized. The protein synthesis needs energy and this energy is carried directly and indirectly by ATP and ADP. When all these proteins and other substances have formed a living organism, the latter is controlled by enzymes which are often directly controlled by a molecule called cyclic adenosine monophosphate, c-AMP. All this shows that phosphorus is essential for the creation of any organism, for its proper functioning and for its reproduction.

Phosphorus is an element which is often limiting for plant growth, since the concentration of plant-accessible phosphorus in soil – free orthophosphate ions PO_4^{3-} – is often very low. Phosphorus as such is not really so scarce, but it exists predominantly in nearly insoluble forms, such as apatite and other metal complexes. The soluble inorganic phosphorus liberated by weathering is to a large extent quickly immobilized by iron and aluminium and sometimes calcium in the soil.

In waters (lakes, rivers and oceans) the phosphate ions are not as easily immobilized since the concentrations of iron, aluminium and also often calcium are much lower in water than in soil. This is one reason why eutrophication poses a problem. Phosphorus, mostly as phosphate ions, – from industrial wastes, sewage and detergents – is often directly discharged into waters, where it is quickly utilized by plants and phytoplankton. If the phosphorus input is large enough, nitrogen becomes limiting for the plants and algae but only for a short period of time; blue green algae and other nitrogen-fixing organisms then start their activity, thereby bringing the system in balance with the elevated phosphorus content. The result is an accelerated plant and plankton growth in the waters – eutrophication. The role and importance of phosphorus in eutrophication is now generally accepted with few exceptions.

Since there are no stable gaseous phosphorus compounds, phosphorus only exists adsorbed on particulate matter in the atmosphere. The atmospheric residence time for phosphorus is short, since particles simply fall down and/or are washed out of the atmosphere by the precipitation.

According to the literature, only Stumm (1973) seemed, earlier, to have tried to quantify a global phosphorus cycle (Fig. 1). The different flows discussed in this compilation are qualitatively shown in Fig. 2. The cycle of flows is dealt with in order from atmosphere, through terrestrial systems and to the ocean, the latter probably being one source for atmospheric phosphorus, thereby closing the circle. Man and his activities are considered as parts of the terrestrial system.

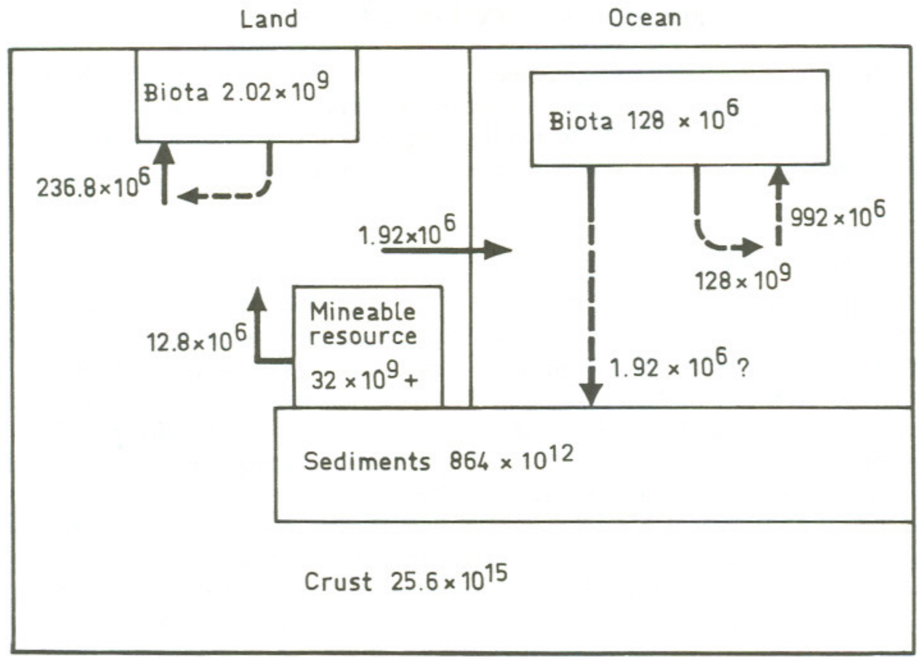

Figure 1. The global cycle of phosphorus compiled by Stumm (1973; redrawn by permission).

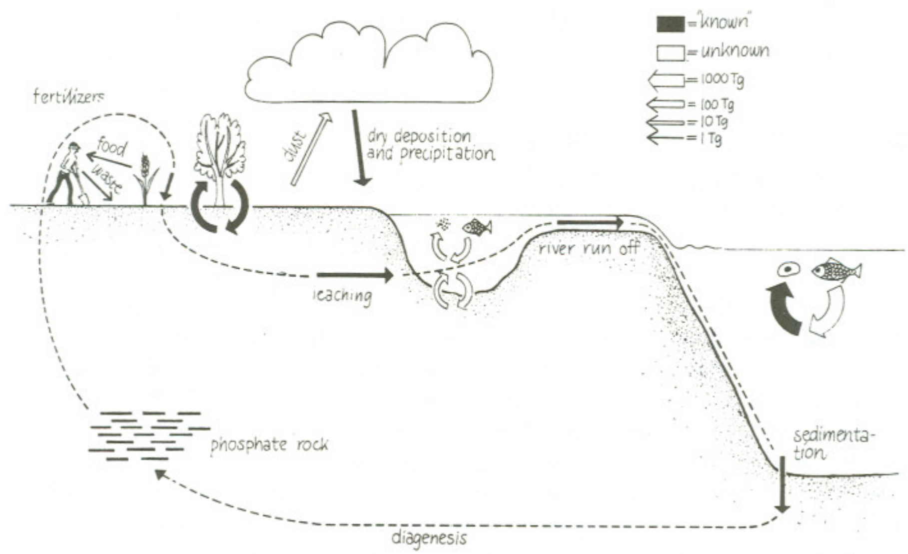

Figure 2. Simplified model of phosphorus fluxes within the global phosphorus cycle. The arrows are roughly proportional to the magnitudes of the flows and also indicating whether the magnitudes are known or not.

PHOSPHORUS IN THE ATMOSPHERE

The atmospheric part of the phosphorus cycle seem to be poorly known. Since phosphorus does not appear in any stable gaseous compound and only exists as adsorbed on particulate matter, the transfers to and from the atmosphere will be less complicated as compared with for instance nitrogen, carbon and sulphur.

Sink mechanisms

The phosphorus fallout over the terrestrial ecosystem has been treated as a single transfer, since there were no indications of how to separate the fallout on vegetation, which may be assimilated before further transport to soil, and direct fallout on soil. Two different values of phosphorus concentrations for terrestrial fallout, dry deposition and rain, have been found: 27 mg P $m^{-2} \cdot yr^{-1}$ for rural areas in Sweden (Odén & Ahl, 1976) and 70 mg P $m^{-2} \cdot yr^{-1}$ (Rigler, 1974). The total land area covers $134 \cdot 10^{12}$ m^2 (FAO, 1975) and the area of rivers and lakes $2 \cdot 10^{12}$ m^2 (Rodin *et al.*, 1974), while the area of terrestrial ecosystems is $132 \cdot 10^{12}$ m^2. The latter value, together with the two rates above, give an estimate of the fallout over terrestrial ecosystems within a range of 3.6–9.2 Tg P yr^{-1}, and within 0.054–0.140 Tg P yr^{-1} over freshwater ecosystems.

The fallout of phosphorus over the marine ecosystem was estimated to be zero by Emery *et al.* (1955). Since dust can very well be transported from land out over the oceans, and since most of the sea-spray is deposited over the oceans, it seems incorrect to neglect this transfer. The phosphorus content in rain was estimated to be 10 μg P l^{-1}, according to Rigler (1974) who states that rain samples usually contains 10–100 μg^{-1} of total phosphorus. The amount of rain over the ocean was calculated by Kalle in 1945 to be $3.47 \cdot 10^7$ l yr^{-1} (Turekian, 1969); a modern estimate is $2.55 \cdot 10^7$ l yr^{-1} according to A. Björkström (pers. comm.). This gives the phosphorus fallout over the oceans of 2.6–3.5 Tg P yr^{-1}, and a total fallout from the atmosphere of 6.2–12.8 Tg P yr^{-1}.

Supplies of phosphorus to the atmosphere

The sources of atmospheric phosphorus were regarded to be high temperature combustion of organic material, exhaust fumes from industries, cremation of human bodies, sea-spray and "lake-spray". The cremation of human bodies was calculated as accounting for 0.002 Tg P yr^{-1} or less. Exhaust fumes from industries also contain only small amounts of phosphorus. Burning of coal gives 0.07 Tg P yr^{-1} (Bertine & Goldberg, 1971), while burning of oil less than 0.01 Tg P yr^{-1}, which was calculated from data provided by K.W. Sedlacek (pers. comm.). High temperature combustion of organic material may therefore give rise to a source strength of about 0.08 Tg P yr^{-1} for the atmospheric content of phosphorus. The freshwater equivalent of sea-spray is probably negligible since the total area of lakes large enough to give rise to this phenomenon and, at the same time, sufficiently nutrient-rich, is indeed very small. Therefore it appears that dust from terrestrial areas and sea-spray are the major sources of phosphorus in the atmosphere. Unfortunately no measurements or estimates seem to have been published on this subject.

PHOSPHORUS CYCLING WITHIN TERRESTRIAL SYSTEMS

In order to compare the flows of phosphorus caused by man's activity in natural ecosystems, the phosphorus cycled within terrestrial systems was separated as follows: the natural part of the terrestrial ecosystem, phosphorus transferred through human biomass and phosphorus affected by industrial activities.

The natural part of the terrestrial ecosystem

The total amount of phosphorus within the terrestrial biomass was calculated from the value of plant biomass, $1.8 \cdot 10^{12}$ metric tons dry weight (d.w.), and other biomass $1.0 \cdot 10^{9}$ metric tons d.w. given by Whittaker & Likens (1973). A phosphorus content of 0.1 % for plant biomass (Bazilevich, 1974) and an estimated value of 0.5 % in other biomass were used, resulting in 1805 Tg P (1800 Tg + 5 Tg).

The transfer of phosphorus from biomass to soil as dead organic matter was calculated to be 136.4 Tg P yr^{-1}. For this calculation, the amount of 25,000 Tg C in dead plant material (Bolin, 1970) was used, together with an estimated carbon/phosphorus ratio of 500/1. The phosphorus in dead animals was calculated using a biomass value of 1000 Tg, assuming half of the animals as being "higher" animals with a mortality rate of 35 % and a phosphorus content of 1 %, and the other half as being insects with a mortality rate of 90 % and a phosphorus content of 0.3 %. Dead plant material thus accounts for 133.3 Tg P yr^{-1} and dead animal material for 3.1 Tg P yr^{-1}.

The uptake of phosphorus by plants from soil has been calculated to be 178 Tg P yr^{-1} by Bazilevich (1974), while Stumm (1973) estimated 236.8 Tg P yr^{-1} including freshwater and marine ecosystems. Food from marine and freshwater ecosystems eaten by wild animals does not seem to have been measured or estimated. The feeding of domestic animals with food from freshwater ecosystems was estimated to be negligible. Domestic animals are fed with food containing 0.020 Tg P yr^{-1} from the marine ecosystem which was calculated from fishery statistics (FAO, 1973a, b), the live weight being reduced by 90 % in order to obtain the dry weight and a phosphorus content of 1 %. The total amount of phosphorus in soil was calculated for the upper 1 metre of the soil profile, which is generally accessible to plant roots. The abundance of inorganic phosphorus on the earth's surface is 0.10–0.12 % (Wazer, 1961). Together with an arbitrary value of soil bulk density of 1 kg dm^{-3} and a land area of 132×10^{12} m^2 (FAO, 1975; Rodin, 1974), the amount of phosphorus in the inorganic fraction of the soil was calculated to be 145,000 Tg P. The phosphorus in the organic fraction of the soil was calculated by using an estimated carbon/phosphorus ratio of 500/1 and two values available for the carbon content. According to Rubey (1951), $7.1 \cdot 10^{5}$ Tg of carbon equals 3800 Tg P, and $30 \cdot 10^{5}$ Tg of C (Bohn, 1976) equals 16,000 Tg P. Since Bohn refers to more recent data than Rubey, Bohn's value was regarded as more probable and the total amount of phosphorus in soil adds up to 160,000 Tg P.

The phosphorus in the soil may be immobilized by iron, aluminium and calcium, becoming non-accessible to plants. There are no values available on this process, probably because it is very hard to measure. Other processes, which diminish the amounts of phosphorus accessible to terrestrial plants are leaching of phosphorus as phosphate ions and erosion of soil containing phosphorus. The leaching of phosphorus from land was calculated to be within a range of 2.5–12.3 Tg P yr^{-1} using the land areas given by FAO (1975) and the available literature values on leaching from different types of soils (Table 1). The erosion of soil containing phosphorus will be discussed later in connection with the river-transfer of phosphorus . Since weathering of rocks containing phosphorus and of immobolized phosphorus in soil is hard to measure, there are no data on this process.

Table 1. Leaching of phosphorus from soil.

Land type	Area ($m^2 \cdot 10^{13}$)	Leaching ($g\ P\ m^{-2}\ yr^{-1} \cdot 10^{-2}$)	References
Agricultural	1.47	a	Olness *et al.* (1975)
		<5	Vollenweider (1968)
		15.6	Nicholls & MacCrimmon (1974)
		18.0	Sawyer (1973)
Permanent meadows	2.99	2–5	Vollenweider (1968)
		3.4	Nicholls & MacCrimmon (1974)
Forests	4.03	<0.9	Singer & Rust (1975)
		<2	Vollenweider (1968)
		10.5	Sawyer (1973)
Other land	4.90	2–5	Vollenweider (1968)

a: value given as <5 % of fertilizers applied per year

The total amount of phosphorus as phosphate rock – or rather the amount of mineable phosphorus reserves – is a rather controversial subject and one where the literature provides the most diverse values. In those papers where the authors have not given their values in metric tons of phosphorus (as P) but in tons of phosphate rock, their values have been recalculated using a mean phosphorus content of 5 % for the world mineable reserves of phosphate rock. The range was then calculated as being 6 500–59,000 Tg P for mineable reserves of phosphorus. The Institute of Ecology (1971) claimed the reserves as being 19,800 Tg P. According to Emigh (1972), the British Sulphur Corporation put the reserves as 6 500 Tg P. Emigh (1972) estimated the reserves to 59,000 Tg P, Stumm (1973) gave a value of 32,000 Tg P, while Goeller & Weinberg (1975) estimated 14,500 Tg P.

The formation of phosphate rock is mainly due to diagenesis of phosphorus-containing sediments in freshwater and marine ecosystems. The time scale for these processes is of the order of 10^8–10^9 years (Broecker, 1974), Discussions have been taking place in recent times on the formation of phosphorites (phosphorus nodules) on the ocean floor, ever since phosphorites became targets for planned phosphorus mining. Most of these phosphorites are old – probably more than 10^5 years old – and are being eroded rather than formed at the present time. Some phosphorites are actually formed at the present time under restricted conditions in a few shallow areas of the ocean (Stumm, 1973). The addition of phosphorus to "phosphate rock" by formation of guano deposits has been estimated to 0.01 Tg P yr^{-1} by Hutchinson (1952).

Phosphorus transfer through human biomass

The total amount of phosphorus in the human biomass was estimated to 0.46 Tg P from a world population of $4 \cdot 10^9$ individuals, a mean weight of 35 kg converted to dry weight by 70 % reduction and a phosphorus content for the human being of 1.1 % (Colbjörnsen, 1973). The amounts of phosphorus turned over by inhumation of human bodies is negligible (approx. 0.002 Tg P yr^{-1}) compared to the amounts of phosphorus turned over as excreta. The amounts excreted are 1.5 g P day^{-1} $capita^{-1}$ as given by Sawyer (1973). From the human excreta of 2.2 Tg P yr^{-1}, 50 % was believed to be used as fertilizers on soil (1.1 Tg P yr^{-1}), 25 % sewered into rivers and lakes (0.55 Tg P yr^{-1}) and 25 % sewered into the ocean (0.55 Tg P yr^{-1}).

Phosphorus ingested by human beings is taken from the terrestrial, freshwater and marine ecosystems. The phosphorus ingested is not only found in directly harvested organic matter, but also in mainly industrially prepared foodstuffs and in pharmaceutical products. In order to calculate the amounts of phosphorus in food from the terrestrial ecosystems, the world agricultural production data from FAO (1975) were used. The phosphorus content of the products was taken partly from Sawyer (1973) and partly estimated on the basis of the phosphorus content of related products according to Sawyer (1973; Table 2).

Table 2. Phosphorus content of global agricultural production. The figures for P-content indicated with an (a) refer to estimates in the present paper while the others to Sawyer (1973)

Product	Production (Tg)	P-content (%)	Amount of phosphorus (Tg)
Wheat	360.23	0.342	1.232
Rice	323.20	0.310	1.002
Maize	292.99	0.110	0.322
Barley	170.86	0.343	0.586
Other cereals	249.58	0.300 (a)	0.749
Potatoes	293.72	0.053	0.156
Other roots	266.16	0.050 (a)	0.133
Pulses	44.13	0.100 (a)	0.044
Soybeans	56.80	0.633	0.360
Vegetables	282.26	0.050 (a)	0.141
Fruits	250.80	0.015 (a)	0.038
Nuts	3.41	0.300 (a)	0.010
Groundnuts	17.59	0.390 (a)	0.069
Vegetable oils	38.89	0.250 (a)	0.097
Meat	115.25	0.225 (a)	0.259
Milk	424.43	0.088	0.374
Eggs	23.19	0.111	0.026
Total			5.57

The proportion of the agricultural products used as human food was estimated to be 40–50 % of the total production, giving a range of 2.2–2.8 Tg P yr^{-1}. Food from freshwater and marine ecosystems was calculated from fishery statistics (FAO, 1973a, b) to an amount of 45.2 Tg "fish" live weight (including algae and crustaceans). This weight was reduced by 90 % in order to obtain the dry weight, of which the phosphorus content was estimated to be 1 %, resulting in 0.045 Tg P yr^{-1} as food from freshwater and marine ecosystems. For pharmaceutical products and other foodstuffs a value of 0.063 Tg P yr^{-1} was estimated by using a phosphate rock mining value of 94.38 Tg (UN, 1974), a phosphorus content for phosphate rock of 13.3 % (Stumm, 1973) and an estimated value of 0.5 % of the phosphate rock being used for the production of pharmaceutical products and foodstuffs. The value of 0.5 % was arrived at by taking the value of 1.3 % for the USA in 1958 (Wazer, 1961), and making the estimation that one-third of the world population consumes 1.3 % and two-third consumes 0.13 %.

Industrial transfers of phosphorus

The industrial use of phosphorus is widespread. Fertilizer industries utilize a great deal. The element is also a common constituent in the production of dyes and surface-active compounds as well as in the production of common detergents. Phosphorus may also be a waste product and sometimes even a by-product in steel-works, since iron often contains phosphorus in varying amounts. Iron ore mines in Sweden and in Lothringen in France contain considerable amounts of phosphorus as apatite iron ores (Hägg, 1969). Since the phosphorus content of slag products from steel-works is approximately 4 % P (Gustafsson, 1974), slag can sometimes be used as phosphorus fertilizer. Waste products from food industries, such as dairy industries and canning industries, contain relatively large amounts of phosphorus. The input of phosphorus into industry was calculated from a phosphate rock mining of 94.38 Tg (UN, 1974) and an average phosphorus content of the phosphate rocks of 13.3 % (Stumm, 1973). Using a value of 85 % (OECD, 1972) for the phosphate rock consumed by the fertilizer industry resulted in 10.7 Tg P yr^{-1} and in 1.9 Tg P yr^{-1} for the remaining 15 % consumed by other industries. In 1972 the production of phosphate fertilizers was 10.43 Tg P (FAO, 1975) and the consumption was 9.93 Tg P (FAO, 1975), the difference indicating a stock of 0.5 Tg P in 1972. The difference between the input of phosphorus to the fertilizer industry and the production of phosphorus fertilizers indicates wastes of 0.3 Tg P yr^{-1} in 1972 from this industry. The wastes from other industries and other activities of man are largely unknown as no measurements seem to have been made, but there is reason to believe that the output of phosphorus from industries, households, etc. would be of the order of 2 Tg P yr^{-1}.

PHOSPHORUS IN AQUATIC SYSTEMS

The total amount of phosphorus in the freshwater biomass was calculated from a plant biomass value of 44.4 Tg d.w. and 12.2 Tg d.w. for other biomass based on the paper by Whittaker & Likens (1973). The phosphorus content of 0.5 % in freshwater plants given by Bazilevich (1974) was used, as well as an estimated phosphorus content of 1 % for other types of biomass. The result was 0.34 Tg P distributed as 0.22 Tg P and 0.12 Tg P respectively. The phosphorus content of detritus and the uptake by phytoplankton do not seem to have been measured. It can be estimated by comparison with the marine ecosystem that these two transfers may be of the order of 10 Tg P yr^{-1}.

Another transfer affecting the phosphorus content of freshwater ecosystems, especially that of biomass, is fish migration (Krokhin, 1975). There are no values of the phosphorus amount transported by catadromous fish, that is fish living in freshwater but migrating to spawn in the ocean (e.g. eels). There are some values on anadromous fish (fish living in the ocean but migrating to spawn in freshwaters, e.g. salmon), such as sockeye salmon (*Oncorhynchus nerka*, Walbaum) in Lake Dalnee and Lake Blizhnee in Kamchatka in the USSR. In Lake Dalnee dead bodies of spawned-out sockeye salmon contributed nearly 26 % to the phosphorus input, while in Lake Blizhnee nearly 20 % over a ten-year period. In certain years phosphorus of marine origin accounted for up to 40 % of the phosphorus input to Lake Dalnee (Krokhin, 1975).

The amount of phosphorus sedimenting in freshwater ecosystems and the amount released from the sediments seem to be unknown. The amounts sedimented are probably less than 1 Tg P yr^{-1} and the amounts released from the sediments even less, since phosphorus is released from sediments only when anoxic conditions prevail in bottom waters and at sediment surfaces.

Phosphorus in river runoff was calculated to be 1.92 Tg P yr^{-1} by Stumm (1973) and 2 Tg P yr^{-1} by Gulbrandsen & Roberson (1973). Although this is not stated in these papers, it seems that these values comprise only dissolved and particulate phosphorus and not the suspended sediments. Emery *et al.* (1955) gave a value of 14 Tg P yr^{-1} including suspended sediments transported by rivers. This figure was recalculated using the amount of sediments annually washed out by the world's rivers (18,290 Tg) given by Holeman (1968), together with a phosphorus content of 0.075 % for sediments, based on data from Emery *et al.* (1955), who gave a sediment loading of 13.7 Tg P yr^{-1}. This latter value of the present denudation rate can be compares with a "natural" denudation rate of 1 metre of soil per 35,000 years estimated on sedimentation rates in inland basins (E.T. Degens, pers. comm.), indicating a sediment loading of 4.6 Tg P yr^{-1}. The additional 9.1 Tg P yr^{-1} in the figure estimated above was believed to represent erosion due to human activities such as deforestation and extensive agricultural activities including tillage and drainage.

The phosphorus content of 35 μg P l^{-1} of the Amazon River (Williams, 1968) would be over 90 μg P l^{-1} if it were corrected for phosphorus loss before analysis according to calculations based on data from Johnson *et al.* (1975). Since the Amazon river is considered relatively poor in nutrients, the mean phosphorus content of the world rivers, excluding sediments, was estimated to be 100 μg P l^{-1}. World river runoff was estimated to be 37,000 km^3 yr^{-1} as a mean of the values given by Turekain (1969) and Bond & Straub (1973). The amount of phosphorus transported with river water would then be 3.7 Tg P yr^{-1}. The total amount of phosphorus in world rifer runoff would thereby be 17.4 Tg P yr^{-1}. The total amount of phosphorus in freshwater, not including biomass and sediments, was calculated to be 90 Tg P, based on a volume of world rivers and lakes of $7.2 \cdot 10^5$ km^3 (Falkenmark & Forsman, 1971) and an estimated mean concentration of phosphorus in world lakes and rivers of 120 μg P l^{-1}. This value was chosen slightly higher than the concentration of the river waters, because of the higher phosphorus concentrations in the hypolimnion of lakes.

The total amount of phosphorus in marine biomass was estimated to 128 Tg P by Stumm (1973). The uptake of phosphorus by phytoplankton in marine ecosystems was calculated to 990 Tg P yr^{-1} by Stumm (1973) and 1300 Tg P yr^{-1} by Emery *et al.* (1955). No values were found for the amount of phosphorus in oceanic detritus; hence it was estimated to be of the same order as the phytoplankton uptake of approximately 1000 Tg P yr^{-1}.

Emery *et al.* (1955) calculated the amount of phosphorus in ocean waters to be 120,000 Tg P and Stumm (1973) gave a value of 128,000 Tg P. The phosphorus content of the sedimented matter in the ocean was calculated by Emery *et al.* (1955) to be 13 Tg P yr^{-1}. The amount of phosphorus released by the sediments in the ocean is unknown, but it is relatively small since the anoxic conditions required for phosphorus release are relatively rare.

The large storage of phosphorus in the ocean and the large internal circulation within the ocean can absorb fairly large additions of phosphorus without any noticeable effect on the concentration of phosphorus in the water. Even if there are relatively small effects on the concentration of phosphorus because of these additions, the fraction of the ocean bottom covered by anoxic waters increases (Stumm, 1973). According to Broecker (1974), the oceanic system may balance this oxygen decrease by changing the dynamics of loss and gain of phosphorus. The reaction time for this is of the order of 10^4–10^5 years. Since a doubling of the phosphorus discharge into the oceans may occur within some decades, there is a risk for an excessive enrichment of phosphorus in the oceans, especially in coastal waters. Low oxygen conditions may therefore be created which eliminate sensitive forms of higher life in these waters.

Man's transport of phosphate rock, fertilizers, meat and cereals may be of importance on a global scale since these transports tend to concentrate the phosphorus in geographically limited areas, where large problems on a regional and local scale may develop. Regionally, man's impact on the phosphorus cycle would produce effects mainly on aquatic systems. The freshwater ecosystem is highly sensitive to additions of phosphorus, whereas coastal waters react only to extra supplies of phosphorus when the water exchange with the ocean is impeded, causing estuarine circulation, for example, in fjords and bays with large freshwater inflows. Areas with estuarine circulation have a tendency to accumulate phosphorus even in a natural state and they also have a tendency to develop anoxic conditions at the bottoms. Even moderate additions of phosphorus to such an area may increase the anoxic conditions and start the eutrophication process. These problems, as well as many of the problems of eutrophication in freshwater ecosystems, are of a local character.

MAIN GLOBAL FLOWS OF PHOSPHORUS – A SUMMATION

A modified scheme showing the main features of the phosphorus cycle is shown in Fig. 3, and the known inventories of phosphorus are listed in Table 3.

The atmospheric part of the phosphorus cycle is largely unknown. There are relatively few data on the phosphorus content of dry deposition and rain; data from the oceanic part of the earth being particularly scarce. All that can be said is that with the data found in this search that the total fallout from the atmosphere would be in the range of 6.2–12.8 Tg P yr^{-1}. The proportions between, for example, dust and sea-spray seem to be unknown.

Table 3. **Phosphorus inventories (Tg P).**

Biomass:	
Human	<1
Terrestrial	1 805
Marine	128
Freshwater	<1
Waters:	
Fresh	90
Marine	120–128,000
Soil:	160,000
Rocks:	
Total solid sphere	$1.1-10^{13}$
Mineable	3 140–9 000

The transfer of phosphorus from the terrestrial biota (not including man) was calculated to be 136.4 Tg P yr^{-1}, while the uptake of phosphorus by plants from soil was calculated to be 178 Tg P yr^{-1} (Bazilevich, 1974) and 236.8 Tg P yr^{-1} (Stumm, 1973). The terrestrial biota receives an addition of phosphorus from the mining of phosphate rock of 12.6 Tg P yr^{-1}. The leaching of phosphorus was calculated to be within the range 2.5–12.3 Tg P yr^{-1}. The amount of phosphorus ingested by man was estimated to be 2.2–2.8 Tg P yr^{-1}, while the amount excreted was calculated to be 2.2 Tg P yr^{-1}.

The uptake of phosphorus by phytoplankton and the phosphorus content of the detritus within the freshwater ecosystem do not seem to have been measured, but by comparing freshwater ecosystems with marine ecosystems, these transfers were estimated to be of the order of 10 Tg P yr^{-1} each. The amount of phosphorus sedimented in freshwater and the amount released from the sediments seem to be unknown, but it was estimated that the amount sedimented is of the order of 1 Tg P yr^{-1} and the amount released even less. Phosphorus transported by rivers to the oceans was calculated to be 17.4 Tg P yr^{-1}.

The uptake of phosphorus by phytoplankton in the oceans was calculated to be 990 Tg P yr^{-1} (Stumm, 1973) and 1 300 Tg P yr^{-1} (Emery *et al.*, 1955). No values were found for the amount of phosphorus in detritus in the oceans, but it is estimated to be of the same order as the phytoplankton uptake, that is approximately 1 000 Tg P yr^{-1}. The amount of phosphorus sedimented in the ocean was calculated by Emery *et al.* (1955) to be 13 Tg P yr^{-1}.

The mean world phosphorus consumption was in 1973 approximately 7 kg P ha^{-1} yr^{-1} (UN, 1974; FAO, 1975), while the use in USA was 10.6, in USSR 5.1, in India 1.7 and in Belgium, 87.3 kg P ha^{-1} yr^{-1}. Considering the exponential increase in fertilizer use (Stumm, 1973) to be limited by prices for fertilizers and transport, by agricultural practices and by effects on the environment, a global maximal rate of 35 kg P ha^{-1} yr^{-1} was estimated. This rate gives a maximal fertilizer production of about

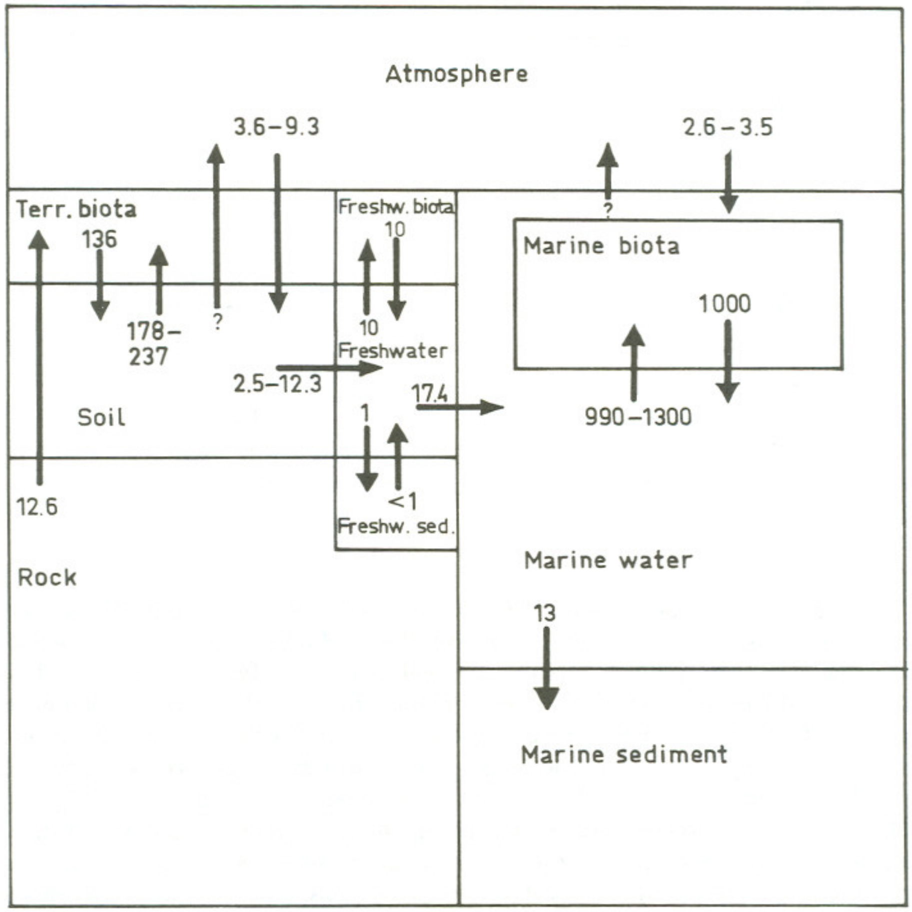

Figure 3. A summary of the global flows of phosphorus ($Tg \cdot yr^{-1}$).

50 Tg P yr^{-1}. Phosphorus reserves will probably not be limiting to man since the size of the mineable phosphorus reserves depends more on prize, or rather on reserves of energy, than on actual geological scarcity.

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