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PROBABLE IMPACTS OF BIOLOGICAL NITROGEN FIXATION ON FERTILIZER USE

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INTRODUCTION: The nitrogen cycle

The nitrogen atom is, in common with atoms of about twenty chemical elements, an essential component of all living things. Like the other "biological" elements (carbon, oxygen, hydrogen sulphur and so on) it undergoes cyclic processes in which it is constantly being built up into living material and degraded again. The nitrogen cycle illustrated in Fig. 1 is a formalization of the Global N budget resulting from the concatenation of many such processes. In it, as in all the cycles of the major biological elements, microbes play a dominant role. Plants, animals and man cannot use the nitrogen gas of the atmosphere directly as a source of N. They obtain their N from their food, which means ultimately from combined N in soil and water. Most of the N-input into the land and waters of this planet originates from the excretions or decomposition of living things. But a net loss of nitrogen to the atmosphere occurs, largely because certain bacteria convert nitrate to nitrogen: the process in the cycle called denitrification (Fig. 1).

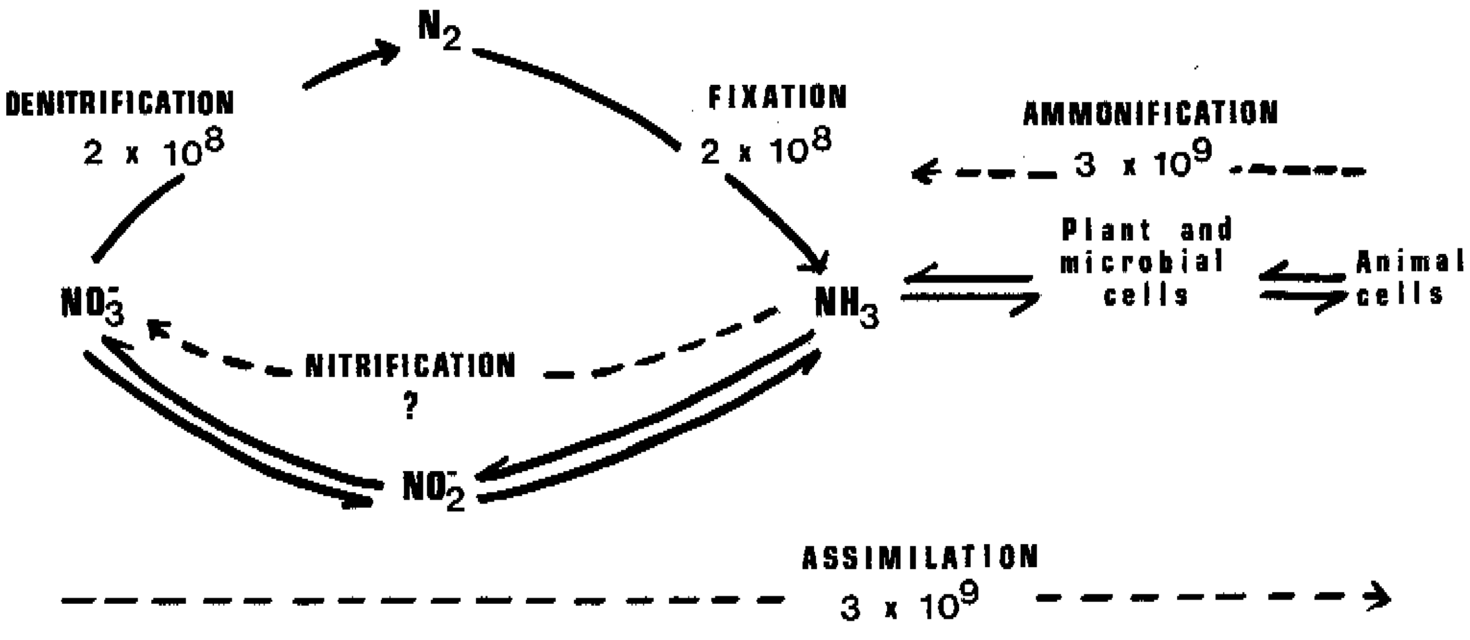

Fig. 1: A simple version of the nitrogen cycle

Nitrates (NO_3^-) in soils and water are converted, via nitrites (NO_2^-) and ammonia (NH_3), into plants and microbes (or rather, into their proteins). Animals eat plants and also each other; man eats both. Thus N becomes assimilated into living matter. Excretion, death and decomposition return N from living matter to the environment as ammonia (a process called ammonification or mineralization) and microbes convert this to nitrites and nitrates. Certain microbes release nitrogen gas (N_2) from nitrates into the atmosphere (a process called denitrification). Most soils contain a reserve of N "immobilized" in the cells of soil microbes; this is slowly released as the microbes die and can then be used by plants. Plants and animals cannot assimilate N_2 but the process called nitrogen fixation, conducted in part by microbes, can recover available N from atmospheric N_2. The numbers quoted in Fig. 1 are estimated turnover rates in tonnes N per year.

Denitrification is compensated for by the process termed "nitrogen fixation", in which nitrogen gas is converted to combined forms which can be utilized in the biosphere. Nitrogen fixation is thus crucial to the persistence of life on this planet.

Nitrogen fixation has three major routes.

Spontaneous nitrogen fixation is the formation of combined nitrogen compounds, nitrogen oxides, in the atmosphere. These dissolve in raindrops and reach soil and waters as nitrites and nitrates. They are formed as a result of electric discharges, UV-irradiation and combustion; the internal combustion engine can make a significant contribution in urban environments. N oxides, with sulphur oxides, are components of "acid rain".

Industrial nitrogen fixation is the industrial production of nitrogen fertilizer from atmospheric nitrogen by the fertilizer industry. Today this is a sophisticated, capital-intensive industry based almost exclusively on the Haber-Bosch process: the catalytic reduction of nitrogen to ammonia, using hydrogen obtained from natural gas.

Biological nitrogen fixation is the conversion of nitrogen to ammonia, and thence cell material, by bacteria. Such bacteria are termed "diazotrophs" and many species of bacteria are capable of diazotrophy, though many more are not. Higher organisms, from fungi to plants and animals, are unable to fix nitrogen. Nitrogen-fixing bacteria often form symbiotic associations with plants; the colloquial term "a nitrogen-fixing plant" is incorrect: such plants are symbiotic associations with a diazotrophic microbe. Symbioses of this kind are ecologically and agriculturally the most important diazotrophic systems.

Recent estimates put the Global N-input by nitrogen fixation around 2.4×10^8 tonnes N/annum. About two-thirds of this input is biological, one quarter as industrial N-fertilizer and the remainder spontaneous. "New" nitrogen introduced by fixation approaches one tenth of the approximately 3×10^9 tonnes of nitrogen incorporated into terrestrial biomass annually; the remainder is recycled fixed N.

Present and future use of N-fertilizer

In parts of this planet where plants and animals are living undisturbed in ecological balance (called "climax" or "equilibrium" eco-systems), biological and spontaneous nitrogen fixation supply a steady input of N and nutrients such as P, K or S tend to limit biomass production. In fringe areas pH, Al toxity or shortage of trace metals such as Mo may be limiting factors. Soon after such areas are disturbed (eg: by flood or fire) or, in particular, are exploited for agriculture or forestry, other elements are recycled rapidly, natural sources of N become scarce and N-fertilizer must be added. There is widespread agreement that the exponential growth of the World's population in the twentieth century (Table 1) has been largely supported by increased N-input into the World's agricultural soils; it is now a familiar truism that an increasing proportion of that input has been as industrial N-fertilizer, a situation which did not exist before the twentieth century.

Table 1: Estimates of the World's population

Year	Number
1500	0.5×10^9
1700	0.7×10^9
1900	1.7×10^9
1950	3×10^9
1978	4×10^9
2000	6.5×10^9
?	7.5 to 8×10^9

The numbers before 1900 are necessarily crude estimates.

The number for 2000 assumes that no Global catastrophe will take place but is otherwise as accurate as the rest, because the parents of those people are already alive. Global population growth is showing a downward trend but the effect will not become significant until the early decades of the next millenium; some social demographers expect a plateau to be reached around 8×10^9 people during the 21st century.

Towards the end of the 1970s, some 30% of the World's population depended on chemical N-fertilizer for its food. The rate of increase of the World's population is declining but, even if all plans for population control are effective, it will double in the early decades of the next millenium (Table 1). To feed that population, the N-input into the World's agricultural products must also double. If chemical fertilizers were the sole means of doubling the input into agricultural products an even greater multiplication of the Global N-fertilizer production would be called for because, with present day agricultural practices, only about 50% of added N-fertilizer reaches the crop. The rest leaches into sub-soil or runs off into waterways and aquifers: the so-called "run-off" problem.

Such an increase in Global N-fertilizer production is not likely to take place for four reasons:

1. The technical sophistication and high capital cost of Haber plants presupposes an industrialized and highly developed society to build and staff the 500 or so new installations which would apparently be needed.

2. The major need for N-fertilizer is in developing countries, so packaging and transport costs, which are energy costs, will be high and will continue to increase.

3. The Haber process consumes fossil energy as natural gas, so competition with other demands for energy will increase the real cost of N-fertilizer and hence of food.

4. Environmental costs result from leaching and run-off. These are often acceptable, being only mild pollution problems, but threats of organic disease, carcinogenesis and damage to the ozone layer may exist. Some of these threats may be exaggerated but others seem real.

While no firm prognostications can be made, it seems to be reasonable to expect that redistribution and, in some countries, mandatory control of N-fertilizer use is likely to occur, for both economic and environmental reasons. Changes in agricultural practice, so that N-fertilizer is used more economically, will be needed and will decrease the proportional demand per unit of product. The development of low technology, low energy, catalytic processes for chemical nitrogen fixation could help to overcome the first three of the problems listed above.

Present and future uses of biological nitrogen fixation

The exploitation of biological processes today involves the use of traditional procedures: growth of clover in grass swards, ploughing-in of legumes, inter-planting of alders in forestry and so on, some of which are used unwittingly. Such traditional farming procedures are still being replaced by the use of N-fertilizer, yet it is obvious that the massive increase in the production, distribution and disposal of chemical N-fertilizer which must be expected could in principle be avoided by increased exploitation of biological nitrogen-fixing systems. Although a return to traditional procedures in unmodified forms is unlikely, this knowledge has led over the past fifteen years to an enormous surge of interest in, and support for, research in diazotrophy, most of which research has, as a long-, medium- or short-term aim, the objective of devising improved ways of exploiting diazotrophy in food and fibre production.

For present purposes one can ask how far any developments arising from this impressive research effort might be expected to influence fertilizer use; the answer, naturally, depends on the character of the advance. Some examples of potential developments follow.

1. Possibilities of immediate applicability: The application in practice of knowledge we already have is now proceeding apace in many countries. For example, most agricultural legumes need little or no N-fertilizer because the nitrogen-fixing bacteria of the genus Rhizobium grow in symbiosis with them in root nodules. Expanded production of grain legumes (eg: soya-beans) compared with cereals saves fertilizer. So does increased use of legumes which are unfamiliar in the Western World (eg: the winged bean, chickpeas, soya protein in human food). Use of the legumes lucerne (alfalfa) or lupins as fodder and/or green manure is on the increase. Azolla, a small water fern which harbours nitrogen-fixing cyanobacteria, is showing enormous potential as a green manure in tropical agriculture (eg: for rice production); considerable success has been achieved in India in developing a farm-based procedure for growing mixed cyanobacteria, which are phototrophic diazotrophs, as green manure. Experiments are in hand to use nitrogen-fixing bacteria to up-grade low N cattle fodder (eg: rice straw). The alder tree has a diazotrophic symbiont and is showing potential for augmenting N-inputs in forestry. In some tropical countries wood, with which to cook food, is becoming scarce and fast-growing trees such as the legume Leucaena or the non-legume Casuarina, both of which are partners in diazotrophic symbioses, are being exploited as rapidly renewable energy sources.

2. Possibilities for the short term: Food legumes specialized to grow in cool or arid zones are being bred in several parts of the World. In the last two decades several new nitrogen-fixing systems, both symbiotic and free-living, have been discovered. They can be associations with grasses, weeds or the leaves of plants. Surveys of such natural nitrogen-fixing systems show promise of revealing exploitable associations with appropriately bred crop plants such as corn, maize or sorghum.

3. Possibilities for the medium term: The augmentation of the effectiveness of existing symbiotic systems by genetic manipulation is now a serious possibility. Mutant diazotrophic bacteria have been obtained which escape regulation of nitrogen fixation (nif) genes by ammonia so that, unlike normal organisms, they go on fixing nitrogen even when the product, ammonia, is present. Such mutants could be exploited for biotechnological ammonia production. The nif genes from Klebsiella pneumoniae, a common soil diazotroph, have been used to render new bacteria diazo-

trophic and might in time be transferred to useful plant or animal symbionts. Genes which determine the effectiveness and specificity of the symbiont Rhizobium have been identified and can be transferred from one strain to another. Such developments could lead to the generation of new or improved exploitable systems in a few years.

4. Possibilities for the longer term: A new technique of plant genetics exists called somatic hybridization. In this procedure, plant cells are treated to obtain bodies called protoplasts. Such protoplasts, when taken from different plants and mixed, can be caused to fuse and form non-sexual hybrids; in some instances entirely new hybrid plants can be regenerated from the fused protoplasts. The process is still at the laboratory stage and so far somatic hybrids have only been regenerated from closely related plants, but in the future it might well be possible to generate new types of plants which combine agricultural desirability with ability to form a nitrogen-fixing symbiosis.

An exciting long-term possibility arises from the successful transfer of nif genes to new bacteria. Bacterial nif genes, or relevant portions thereof, could be introduced into the genomes of a crop plant. If other necessary genetic information were also successfully introduced, so that the plant could read and use the genetic information encoded in nif, the plant would be able to fix its own nitrogen: it would have become independent of both microbes and of chemicals as far as N-input is concerned. Problems of localization, expression, regulation and stabilization of nif genes in the plant host would have to be overcome, but research in this area has revealed no fundamental reasons why it should not be done successfully. Cereals are the World's primary food crop so, if a useful cereal proved to be a feasible host, the consequences for World food production would be tremendous. However, it is a long haul from a laboratory system to an agriculturally exploitable, nitrogen-fixing plant and, though the possibilities discussed in this paragraph are already over the horizon, they are still at least two or three decades away.

Probable impact on fertilizer use

It is an inescapable truth that, short of a Global catastrophe, the demand for N-fertilizer, biological or chemical, will continue to increase. Thus the need for supplementary fertilizers such as P, K and S will increase more or less concomitantly. It is impossible to make quantitative estimates with any precision, because local needs will depend on local reserves of these nutrients, but if a ratio of N:P:S:K = 10:2:1:5 is taken as a rough guide to the element content of agricultural crops, then the Global demand for these nutrients will increase proportionately with the demand for N. Of course, increased N-inputs are likely to reveal other limitations, as the switch away from sulphate of ammonia as an N-source has revealed unsuspected S-deficiencies during the last two decades. As new areas of land are brought under agriculture or forestry, demands for fertilizers which include a soil-conditioning function (eg: lime or native sulphur) are likely to increase; minor nutrients (eg: Mo, Co) may become locally important.

The major impact of biological nitrogen fixation is likely to be on demand for N-fertilizer. Yet even here there would seem to be no serious prospect of a decline in demand. It is unlikely, at least over the next few decades, that increased exploitation of biological nitrogen-fixing systems will do more than slow down the rate of increase in demand for N-fertilizer. The escalating costs of chemical fertilizer will undoubtedly affect the availability of N-fertilizer to developing countries and, since it is fundamentally an energy cost, it is unlikely that this trend will cease over the same period. Yet the energy cost of N-fertilizer in the U.S.A., which is a third of the energy cost of U.S. agriculture at the farm gate, is still only 1% of that country's energy budget. Despite their increases, the energy costs of fertilizer production and distribution are small in relation to the total energy demands of developed countries. These considerations lead one into political areas: it may well be that mandatory controls of fertilizer use and distribution will become necessary and it is highly likely that economies in its use will be made, with beneficial environmental effects, at least locally.

However, the soils of this planet will be obliged to accept, over the next few decades, a very substantial increase in N-input. Dr. R.W.F. Hardy calculated in 1974 that some 500 new Haber plants would be needed to double World cereal output using only additional chemical fertilizer. But undoubtedly the biological component of the necessary N input will increase. As well as being lower in monetary costs, both the energy and environmental costs of biological nitrogen inputs are generally less than those of chemical inputs (though such costs are by no means eliminated, for legumes are less efficient converters of solar energy into product (0.1 to 0.2%) than cereals (0.3 to 0.4%), and their residues certainly cause run-off problems. So the social, political and economic pressure towards increased exploitation of biological nitrogen fixation will be strong, with a consequent trend towards a decline in the rate of increase in demand for industrial N-fertilizer; this is already happening to a modest extent. A more quantitative assessment of the impact of biological nitrogen fixation on the use of N-fertilizer cannot be attempted, because it depends on the success of research on the various possibilities outlined in this paper.

CONCLUSION

Biological nitrogen fixation is not likely to influence the upward trend in demand for non-nitrogenous fertilizers consequent on the continued expansion of the World's population. It will influence the demand for industrial N-fertilizer only marginally in the next few years, but lowering the rate of increase of demand, and economies in use of N-fertilizers are likely to have a greater, yet still marginal, effect. In the longer term, genetically improved biological systems might make more substantial inroads on the demand for N-fertilizer, but a downward trend is unlikely unless efficient diazotrophic associations with cereals are developed by genetic manipulation.

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TA/82/14 Probable impacts of biological nitrogen fixation on fertilizer use, by J. POSTGATE (University of Sussex, United Kingdom)

DISCUSSION : (Rapporteur L.J. CARPENTIER, IFA)

Q - Mr. K.H. WALTER, Adelaide & Wallaroo Fertilizers Ltd, Australia

In view of the fact that sulphate is easily leached from the soil and that legumes require as much sulphur as phosphorus, it appears to me that the manufacture of sulphur free fertilizers is unwise.

1. If your research is successful, does it mean that this could lead to a decline in demand for sulphur free fertilizers?

2. What micronutrients did you add to your agar medium?

A - I believe that the use of sulphur-free fertilizers is already disclosing hitherto unsuspected sulphur deficiencies in soils in various parts of the world. Successful development of biological systems which require little or no fertilizer N can be expected to have a similar effect, because the systems will require normal amounts of S.

A - Our laboratory media for nitrogen-fixing bacteria contain K, P, S, Mo, Fe and undoubtedly traces of Cu, Ni, Co and so on... as impurities in the reagents. Some bacteria require Ca.

Q - Mr. F.P. ACHORN, Tennessee Valley Authority, USA

Corn Crop - About 50% of chemical nitrogen applied is not used by corn crop. Of the 50% that is not used half is usually fixed as organic nitrogen in the soil and the other is lost in run-off.

Is their a way to fix more nitrogen in the soil and eliminate nitrogen run-off?

A - Three ways are available in principle of minimizing the leaching/run-off problem:

(1) Use ammonia, which binds tightly to soil, as the N fertilizer, together with an inhibitor of nitrifying bacteria. The inhibitor delays formation of the very mobile nitrate and allows the plant longer to "catch" the available N.

(2) Fertilize the soil with small, graded pulses of N over the growing season.

(3) Use a "slow release" N fertilizer graded to the crop's requirements.

None of these strategies is economic on a global scale although they can be very effective in special cases.

Q - Mr. L.J. CARPENTIER, IFA

First I have two small points of clarification to make:

1. On page 5 of your paper you mention an N:P:K:S ratio of 10:2:1:5.

   Did you take into account the rate of utilization of the various nutrients, in particular, phosphorus?

2. On page 6 of your paper, you state that residues of legumes can cause run-off problems.

   Can you elaborate on that statement?

Q - 3. The next question is of a more general character.

Biological nitrogen fixation has raised a lot of interest among international circles, the public, in particular among developing countries. FAO for example is currently seriously involved. From your paper, as well as from Prof. Hess's, it appears that there will be no very significant breakthrough in the near future. Don't you think something should be done to avoid disappointing the great expectations put in these new developments?

A - 1. No. These numbers are simply mean steady-state compositions.

2. Legumes subject to trauma (eg: eaten by cattle, or cut for cropping) release N (and other nutrients) into the environment. This goes through the normal cycle and can leach or run-off as nitrate.

   A common example is newly cut lucerne, which can release substantial N. Biological nitrogen fixation is not a panacea for environmental problems, but in principle it appears more controllable.

3. I think meetings such as this serve to present a more balanced view of the position. In my experience, the uncontrolled excitement of the mid-seventies has died down and, though some publicists will exaggerate, wiser views now prevail among scientists and technicians. Undoubtedly biological fixation has an increasingly important part to play in world food production, but no sudden or dramatic changes can be expected at the field level.