Bio Factsheet

April 1998 Number 18

The Nitrogen Cycle

All living organisms need a source of nitrogen in order to synthesise molecules such as DNA and proteins. This Factsheet will summarise how plants and animals obtain that nitrogen.

At first glance, it might seem very easy for plants to obtain their nitrogen; the atmosphere contains 78% by volume of nitrogen and this is easily the most abundant gas in the atmosphere. However, atmospheric nitrogen is, in fact, unavailable to plants or animals and only some specialised micro-organisms are able to use this huge potential source. Plants usually obtain the nitrogen they need by absorbing nitrate ions or ammonium ions through their roots. However some plants obtain much of their nitrogen by forming a symbiotic relationship with nitrogen fixing bacteria.

Nitrogenous compounds may be added to the soil through:
(i) artificial fertilisers
(ii) weathering of rocks
(ii) acid rain
(v) lightning.

Nitrogenous compounds in the soil may be volatilized back into the atmosphere, washed down through the soil (leached) into sub-surface supplies, taken up by plants, broken down by micro-organisms such as bacteria, or they may remain fixed in the soil beyond the rooting depth of most plants.

The nitrogenous compounds which are taken up by plants are **assimilated** into nitrogen-containing tissues (eg. lignin) and into molecules such as chlorophyll. Herbivores then obtain their nitrogen by eating plants, and carnivores obtain their source of nitrogen by eating the herbivores or each other. Both animal and plants return nitrogen to the soil via their excretory products and when they die and are decomposed. In addition, animals release nitrogenous compounds to the soil through their faeces. Thus, the movement of nitrogen from the atmosphere to soil to plants to animals to soil and to atmosphere forms a **cycle**. We now need to look in more detail at each of these of these individual steps.

1. Nitrogen fixation

Nitrogen fixation is the conversion of nitrogen gas into ammonia (NH_3). This is carried out by nitrogen fixing bacteria such as **Rhizobium**, **Azotobacter** and **Frankia** (the latter in alder trees) as well as some cyanobacteria such as **Nostoc** (Table 1)

Table 1. Nitrogen-fixing organisms

Name of organism	Where it lives
Rhizobium	root nodules of leguminous plants
Azotobacter	aerated soil
Clostridium	anaerobic soils
cyanobacteria, eg. *Nostoc*	wetlands

As can be seen from Table 1, some nitrogen fixing species live freely in the soil. However, most live in a mutually beneficial (mutualistic) relationship with a plant. Rhizobium, for example lives freely in most soils where it can carry out nitrogen fixation. However, most nitrogen fixation by Rhizobium occurs inside the roots of legumes such as clover and beans. The invasion of the root hairs by Rhizobium stimulates the root cells to divide and form nodules. Inside the nodules, Rhizobium fixes the nitrogen gas which diffuses in across the root hair. This is achieved using the enzyme **nitrogenase**, which only works under anaerobic conditions. Nitrogen fixation requires a lot of energy to carry out and this is one reason why only very specialised organisms can do it. Because of this, nitrogen in a biologically useful form is often in short supply in ecosystems and is frequently the factor which limits overall productivity.

2. Nitrification

The decomposition of dead plants and animals, and their wastes releases ammonia into the soil. This may then be transformed into nitrite and then nitrate ions by bacteria such as Nitrosomonas and Nitrobacter respectively. This process is known as **nitrification** (Fig 1).

Fig 1. Nitrification

ammonia NH_3 —Nitrosomonas / Nitrococcus→ Nitrite ions NO_2^- —Nitrobacter→ Nitrate ions NO_3^-

Nitrosomonas, Nitrococcus and Nitrobacter are therefore examples of **nitrifying bacteria**. Note that these are oxidation reactions and that these bacteria are using the nitrogen compounds as their source of energy i.e. they are **chemoautotrophs**. Thus, the action of nitrifying bacteria makes nitrate ions available in the soil which can then be absorbed by plant roots.

3. Absorption and assimilation

Nitrates are actively absorbed across root hairs i.e. ATP is required. Nitrate and or ammonium ions are then **assimilated** by the plant i.e. they are used to build complex nitrogen-containing substances such as nucleic acids or amino acids, which can then be used to build tissue. If these tissues are then eaten by animals, the complex nitrogenous substances are digested i.e. made into simple soluble molecules which can be absorbed across the animal's gut before, in turn, being assimilated into animal tissue.

4. Denitrification

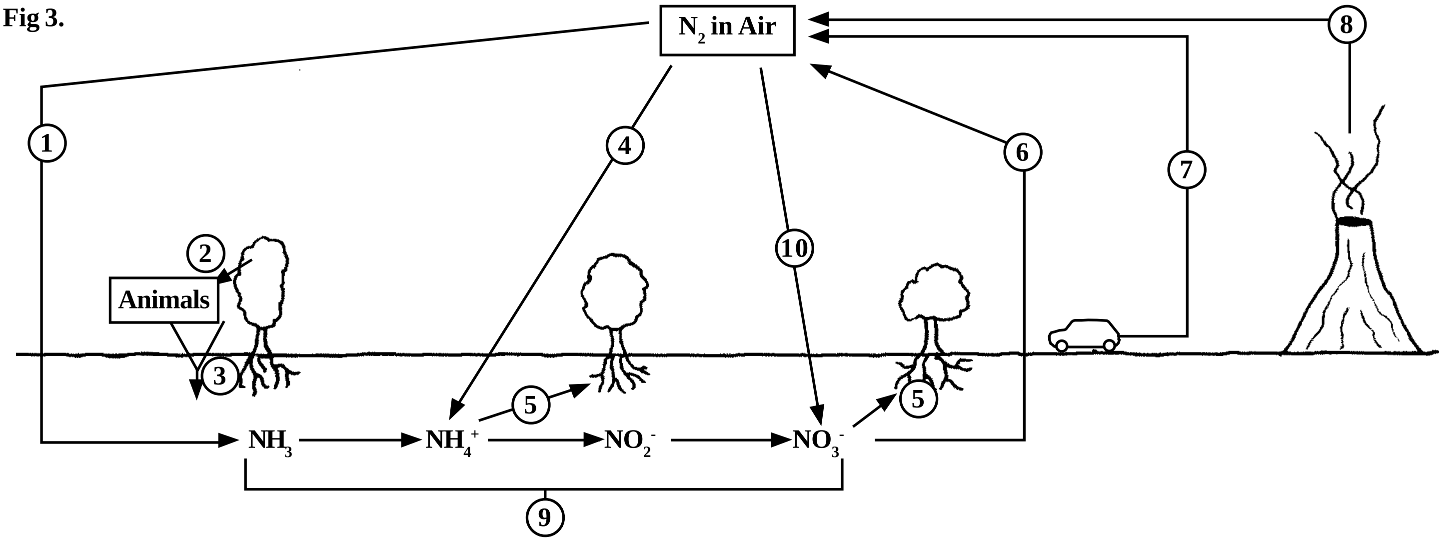
The cycle would not be complete unless some nitrogen was released back into the atmosphere. This occurs as a result of the actions of **denitrifying** bacteria i.e. bacteria which utilise NO_3^- as an energy source and convert it back into nitrogen gas (Fig 2) or dinitrogen monoxide (N_2O).

Fig 2. Denitrification

ammonia NH_3 —eg. Pseudomonas denitrificans / eg. Thiobacillus dentrificans→ Nitrogen N_2

Denitrification occurs in anaerobic conditions. The most common cause of anaerobic conditions in agricultural soils is through water-logging, where the soil spaces, which are normally occupied by air, become filled with water. Under these circumstances, denitrifying bacteria will rapidly convert nitrate ions into nitrogen gas which will diffuse out of the soil and back into the atmosphere. It is clearly essential that farmers try to do everything they can to avoid anaerobic conditions within their soils. Ploughing and draining are the most common techniques. The nitrogen cycle is summarised in Fig 3.

Fig 3.



1. Nitrogen fixation by free-living soil bacteria
2. Animals get their nitrogen by eating plants
3. Nitrogen released into soil by decomposition and via waste products
4. Haber Process
5. Plants take up nitrogen as NH_4^+ or NO_3^-
6. Denitrification
7. Exhaust fumes release N_2O/NO_2
8. Volcanoes release NH_3 into the atmosphere
9. Nitrification
10. Lightning

Humans and the nitrogen cycle

1. Using the **Haber** process, humans annually produce millions of tons of nitrogen-containing fertiliser. This process requires high temperatures and pressures which are generated using the energy from fossil fuels.

2. However, it is estimated that 50% of nitrogen fertiliser applied to fields does not end up in the crop - instead, it is lost through volatilization, denitrification, run-off, erosion and leaching. In areas such as East Anglia, nitrate concentrations in underground water supplies regularly exceed the EU limit of 50mg per litre. High nitrate levels in drinking water cause two problems:

(a) In infants under 3 months old, nitrates are converted to nitrites which enter the bloodstream. There they convert the ferrous (Fe^{2+}) ion of haemoglobin into the ferric (Fe^{3+}) form which prevents the haemoglobin carrying oxygen. The consequence - **methaemoglobinaemia** or **blue baby syndrome** - is characterised by cyanosis of the lips and skin, shortness of breath and eventually suffocation.

(b) Nitrates may be reduced to nitrites by bacteria in adult saliva. Nitrites then combine with amines to form carcinogenic **nitrosamines**. Thus, high nitrate concentrations have been linked to the increasing incidence of gastric, urinary and bladder cancers.

3. High levels of nitrates in aquatic ecosystems can lead to **eutrophication**. High nitrate concentrations result in algal blooms. As the algae die their decomposition by bacteria creates a huge biochemical oxygen demand (BOD), oxygen concentrations fall and aerobic organisms may die.

4. The increased use of nitrate fertilisers leads to increased denitrification which can release dinitrogen monoxide (N_2O) into the atmosphere. Dinitrogen monoxide can give rise to nitrogen monoxide (NO) which sets off a series of reactions which end with the destruction of the stratospheric ozone layer. This ozone layer protects us from carcinogenic UV radiation, so increasing nitrate fertiliser use is linked to increasing skin cancer. Dinitrogen monoxide is also a **greenhouse gas**, contributing to the warming of the lower atmosphere (troposphere).

5. Nitrogen dioxide (NO_2), from the combustion of fossil fuels, stimulates the production of ground level (tropospheric) ozone which is a respiratory irritant and which reduces resistance to bacterial infection. Both NO_2 and N_2O combine with volatile organic compounds and carbon monoxide in sunlight to produce **photochemical smog**.

6. Nitrogen oxides released from the combustion of fossil fuels form nitrous and nitric acid in the atmosphere which are major contributors to **acid rain**. Acid rain damages aquatic and terrestrial ecosystems and is another example of a natural phenomenon being made much worse by human activity.

Exam hint - *Candidates are often asked to show that they understand the economic implications of biological processes - denitrification is a good example.*

Exam Questions on nitrogen fixation

Common questions focus on:

1. **Simple labelling and interpretation of the nitrogen cycle diagram**. Once you have understood each of the major processes in the nitrogen cycle, you should relentlessly practice drawing the diagram so that you can do it off by heart.

2. **The benefits which the bacterium and the green plant derive from their symbiotic relationship in nitrogen fixation**. Bacteria gain sugars produced by the plant during photosynthesis and the plant gains a source of utilisable nitrogen.

3. **The way in which root nodules create and maintain the anaerobic conditions necessary for the functioning of nitrogenase**. The invasion of bacteria causes the plant to form nodules. Within the nodules, bacteria rapidly multiply forming **bacteroids**. The bacteroids carry out nitrogen fixation using nitrogenase. The plant produces **leghaemoglobin**, a pigment which absorbs any free oxygen, thus allowing the bacteroid enzyme to function efficiently.

4. **The potentially important economic uses of the processes of nitrogen fixation**. For example, alder trees contain nitrogen fixing bacteria. These bacteria fix atmospheric nitrogen and make large quantities of utilisable nitrogen available to the plant. However, they also excrete amino acids into the soil, thus dramatically increasing the fertility of the soil. This makes them invaluable in, for example, reclamation projects on derelict land such as coal spoil heaps.

5. **The possibility of transferring the genetic information controlling nitrogen fixation into crop plants such as wheat and rice etc.** - This would greatly increase world food production, reducing the need for expensive and polluting nitrogen fertilisers. The major difficulty here is that the synthesis of nitrogenase is controlled by not one but by seventeen different genes i.e. a gene complex.

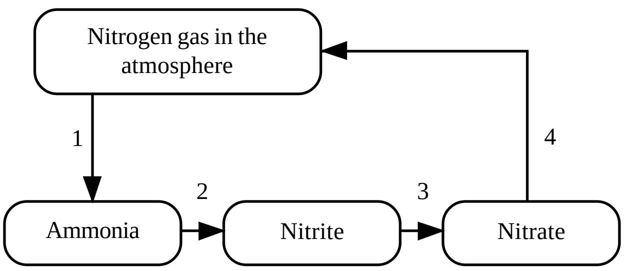
Practice questions

1. Plants require a source of nitrogen to produce certain compounds. Name **one** of these compounds. (1 mark)

2. Animals are not essential to the nitrogen cycle, explain why. (4 marks)

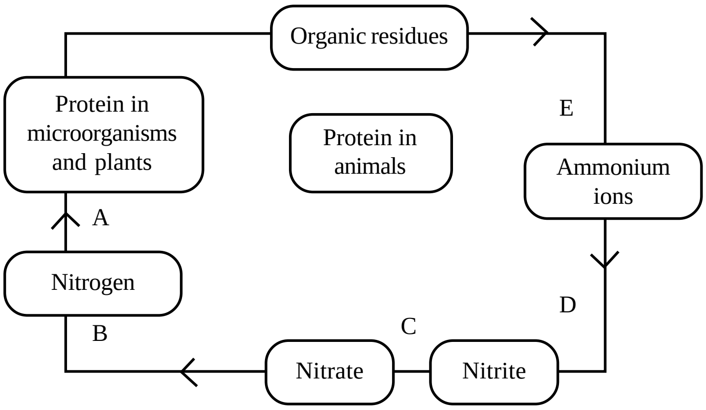
3. Large quantities of nitrate may drain from agricultural land into freshwater lakes. Describe the biological consequences of this. (4 marks)

4. Part of the nitrogen cycle is shown in the diagram below.



Name a genus of bacteria which is responsible for each of the reactions 1, 2, 3 and 4 (4 marks)

5. The following diagram summarises the nitrogen cycle.



Give the letter of one stage which involves the following microorganism:

(a) denitrifying bacteria
(b) nitrogen-fixing bacteria
(c) nitrifying bacteria
(d) saprophytic fungi

(4 marks)

Answers

1. ATP/DNA/RNA/Chlorophyll;

2. bacteria fix nitrogen;
   in soil/legumes;
   bacteria return nitrogen to atmosphere;
   plants obtain their nitrogen from the soil or via fixation;
   nitrogen can be recycled solely by plants;

3. Algal bloom;
   Reduces light penetration to lake bed;
   macrophytes die;
   dead algae broken down by aerobic bacteria;
   create high BOD;
   O_2 consumed;
   aerobes die;
   eutrophication;

4. 1: Rhizobium;
   2: Nitrosomonas/Nitrococcus
   3: Nitrobacter;
   4: Thiobacillus/Pseudomonas

5. (a) B;
   (b) A;
   (c) D/C;
   (d) E;

Acknowledgements;
This Factsheet was researched and written by Kevin Byrne
Curriculum Press, Unit 305B, The Big Peg,
120 Vyse Street, Birmingham. B18 6NF

ISSN 1351-5136