In many parts of the world the landscape is managed by humankind for food production, forestry and recreation or merely for its beauty. For each of these uses the plants that are grown require appropriate levels of many different nutrients. This booklet considers the essential need for phosphorus in agriculture.

efma

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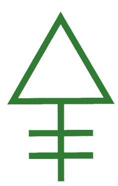
Phosphorus was probably discovered about 1669 by the German alchemist H. Brandt in Hamburg.

The word phosphorus is derived from the Greek "phos" meaning "light" and "phorus" meaning "bringing".



Alchemist symbol for phosphorus

Contents

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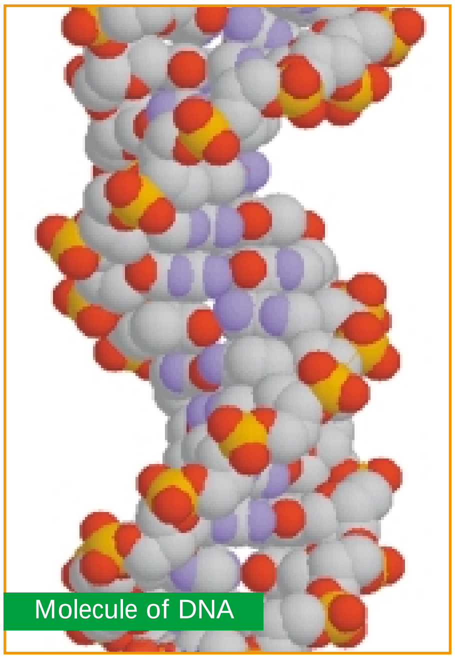
Introduction

Phosphorus (P) is essential to all known life forms because it is a key element in many physiological and biochemical processes. A component of every cell in all living organisms, phosphorus is indispensable and cannot be replaced by any other element. Phosphorus occurs in complex DNA and RNA structures which hold and translate genetic information and so control all living processes in plants, animals and man. It is an essential component of the energy transport system in all cells.

The element phosphorus does not occur by itself in nature. It is always combined with other elements to form phosphates. Phosphates can be very complex and more than one form of phosphate will be found in soils, water, plants, animals and man. In this booklet, therefore, the word "phosphorus" will be used in the text rather than identifying the particular phosphate but, in most cases, numerical values will be given as P_2O_5 (2.29 kg P_2O_5 is equivalent to 1.0 kg P).

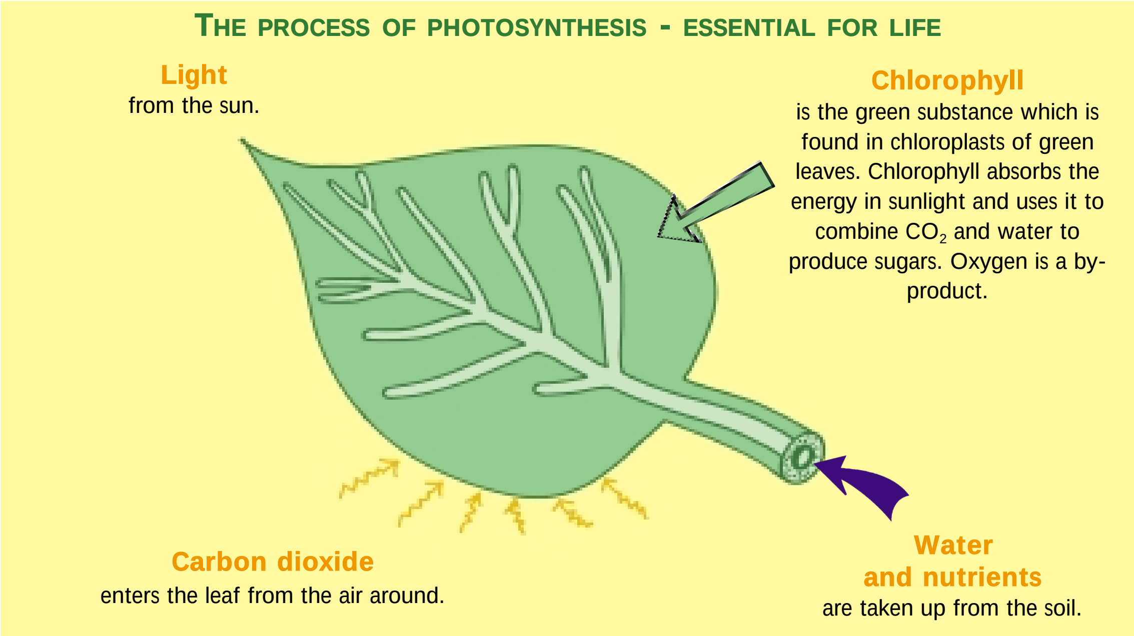
Phosphorus in plants

Phosphorus is essential for photosynthesis, the process by which plants harvest energy from the sun to produce carbohydrate molecules, i.e. sugars. These are transported to the plants' storage organs such as the root of sugar beet or the grain of wheat, rice, maize and the potato tuber where the sugars are converted to starch. This process is essential to all life, and is the first step in the chain to produce food, feed and fibres.



Molecule of DNA

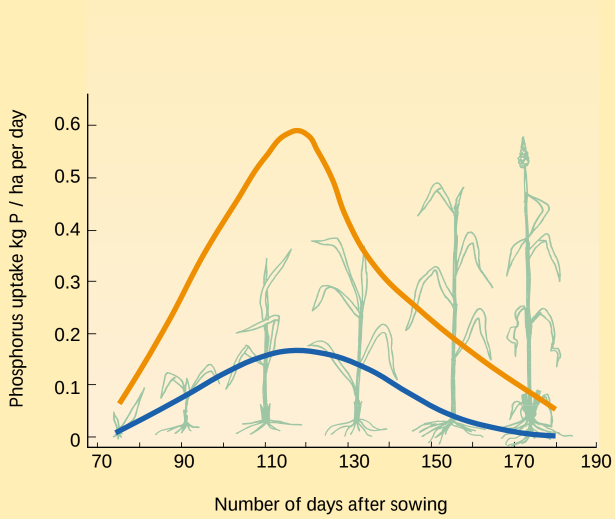
Picture: IACR Rothamsted



Phosphorus is one of the primary structural components of membranes that surround plant cells. It is involved in the synthesis of proteins and vitamins and occurs in important enzymes.

Phosphorus is taken up by plant roots from the water in the soil, the soil solution.

Pattern of P uptake by spring barley



Source: Adapted from Leigh and Johnston 1986.

The uptake of phosphorus changes during crop growth. Spring barley amply supplied with phosphorus took up about 1.4 kg P_2O_5 (0.6 kg P)/ha per day (orange line) whereas a crop with little available phosphorus took up about 0.4 kg P_2O_5 (0.2 kg P)/ha per day (blue line). Yields of grain reflected phosphorus availability, 6.4 and 2.9 t/ha with and without an adequate supply of phosphorus.

Delayed ripening of barley (left).

Box 1

Examples of phosphorus content in crop products, in grams P_2O_5 per kg fresh weight

Wheat	7.8
Rice	6.0
Sprouts (buttons)	2.6
Peas (vining)	1.7
Cauliflower	1.4
Beans (French)	1.0
Potatoes	1.0
Carrots	0.7

However, phosphorus compounds are not very soluble, and therefore the amount of plant available phosphorus in the soil solution tends to be far less than the plant requires, particularly when it is growing vigorously. In consequence, the phosphorus in the soil solution may have to be replenished as often as ten times each day in these periods.

On a daily basis, a rapidly growing crop may take up the equivalent of about 2.5 kg P_2O_5 per hectare (ha, i.e. 10,000 m^2). It is clear, therefore, that there must be adequate, readily available reserves of phosphorus in the soil. Most unmanured soils contain too little readily available phosphorus to meet the large demand of crops, particularly during certain periods of the growing cycle. Fertilizers containing phosphorus must therefore be added.

A deficiency of phosphorus affects not only plant growth and development and crop yield, but also the quality of the fruit and the formation of seeds. Deficiency can also delay the ripening of crops which can set back the harvest, risking the quality of the produce.

To successfully produce the next generation of plants, seeds and grains must store phosphorus so that the seedling has enough to develop its

Purple leaves signify phosphorus deficiency.

first roots and shoots. Then, as the root system develops, the growing plant will be able to take up the phosphorus it requires from the soil, providing there are adequate reserves.

Phosphorus in humans and animals

Humans and animals also need to obtain an adequate supply of phosphorus from their food and feeding stuffs. Phosphorus deficiency affects many of the essential processes on which the life of an animal depends, just as it does in plants. Phosphates are added to the diet of pigs and poultry to ensure they do not suffer any deficiency, and to prevent health problems, weak bones and impaired fertility.

Box 2

Recommended daily intake (RDI) of phosphorus for humans, g P_2O_5/day

Children	1.1
Adults	1.6
Pregnant and lactating women	2.1

Source: National Food Authorities in various European countries

Because much of the phosphorus ingested by animals is excreted in the faeces, animal manures, when properly used, are valuable sources of phosphorus.

Phosphorus is the second most abundant mineral element in the human body (the first is calcium), accounting for more than 20 percent of the body's minerals. Calcium phosphates, for example, are the major constituent of the skeletal bones and teeth and contain 85% of the body's total phosphorus. Lack of phosphorus not only affects bone structure, but also appetite, growth and fertility.

Box 3

Examples of phosphorus content in food, in grams P_2O_5 per kg fresh weight

Cheese (hard)	11.6
Fish	5.7
Meat	4.7
Egg	4.1
Bread (wheat)	3.4

Source: United States Department of Agriculture (USDA) Nutrient Database

The occurrence of phosphorus in nature

Phosphorus is not a rare element. It is eleventh in order of abundance in the earth's crust but the concentration in many rocks is very small. However, there are deposits which are sufficiently rich in phosphorus that extraction is commercially viable. Phosphate rock deposits are found throughout the world and over 30 countries are currently producing phosphate for use in domestic markets and/or international trade.

The main commercial deposits at present are in the United States, Morocco and West Africa, China, the Former Soviet Union and South Africa. The three major producing countries, i.e. the USA, China and Morocco currently produce approximately two thirds of the global phosphorus requirement. Morocco, whose reserves amount to an estimated 50% of the world total, also has potential reserves and natural resources which are estimated to represent around 60% of total world resources. The only commercial West European deposit is in Finland.

Reserves and resources of phosphorus

Since phosphorus is essential for all living processes, there is concern that the exploitation of this non-renewable resource to meet current demand is not sustainable. It is very important, however, to make a distinction between reserves, i.e. deposits which can currently be exploited in an economically viable way, and resources (or potential reserves), i.e. deposits which could be used, subject to advances in processing technology or the value of the finished product.

Estimating reserves is not easy for a number of reasons. Estimates are often based on different criteria; a country or company may consider its estimated reserves confidential and commercially sensitive; possible future changes in technology and costs of production are very difficult to forecast; and there is no certainty about future rates of consumption. It is

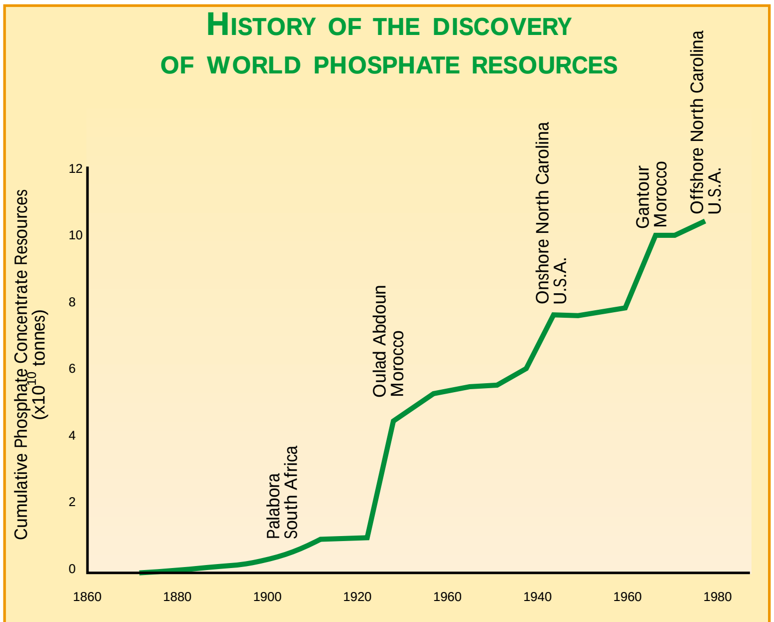
Box 4

Phosphate rock production, 138 million tonnes (Mt) total production in 1999 estimate

United States	30%
Morocco	17%
China	14%
FSU	8%
Israel and Jordan	7%
Tunisia	6%
Brazil	3%
South Africa	2%
Others	13%

Source: United States Geological Survey web site

Mining sedimentary phosphate rock in Morocco.
Photo: A.E. Johnston



Source: The Fertilizer Manual.

therefore difficult to say just how long the world's phosphate supply might last. Estimates of current reserves that can be exploited vary from 250 years to as little as 100 years. If known potential reserves are taken into account, the forecast may be as long as 600-1000 years. This does not include the possible discovery of "new" phosphorus resources. Yet, however large or small the reserves/resources may be, they are finite and must be used efficiently and in a sustainable way.

Mining igneous phosphate rock in Finland. Photo: Kemira

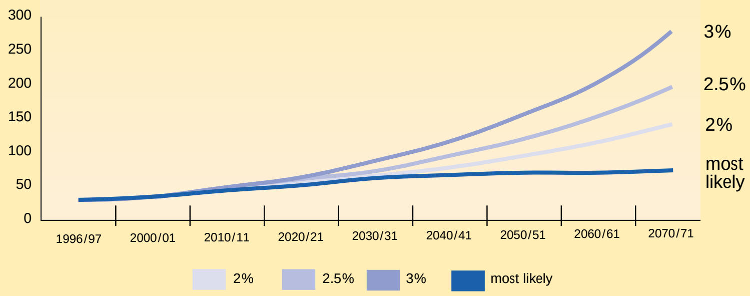
Two major opportunities for increasing the life expectancy of the world's phosphorus resources lie in recycling by recovery from municipal and other waste products and in the efficient use in agriculture of both phosphatic mineral fertilizer and animal manure.

The main uses of phosphorus

At present there are three main uses of phosphorus. In Western Europe some 79% is used to make fertilizer for use in agriculture for food production, around 11% is used to make feed grade additives for animal feeding stuffs, and approximately 7% is used to make detergents. The remainder is used in speciality products as diverse as additives for human food and metal surface treatments to delay corrosion.

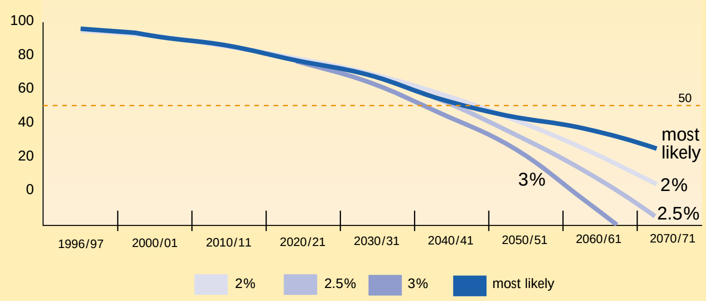
PHOSPHORUS ESSENTIAL ELEMENT FOR FOOD PRODUCTION

SCENARIOS OF P_2O_5 CONSUMPTION



Source: Phosphorus and Potassium No 217.

LIFETIME OF RESERVES



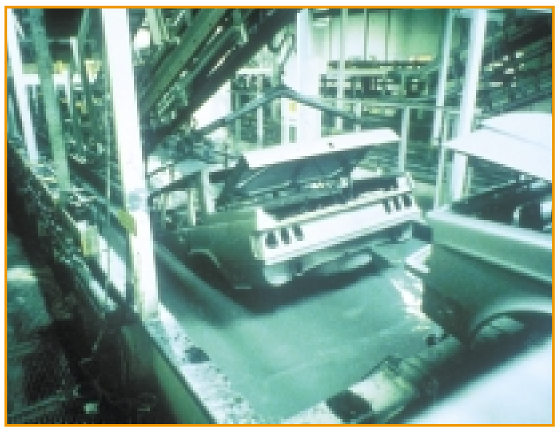
Source: Phosphorus and Potassium No 217.

Relationship between various scenarios for P_2O_5 consumption and the lifetime of reserves, assuming 2%, 2.5%, 3% and the most likely increase in P_2O_5 consumption.

Box 5

Phosphorus uses in Western Europe

Fertilizers	~79%
Feed additives	~11%
Detergents	~7%
Other applications	~3%



Phosphorus in Agriculture

The need for phosphorus in agriculture

Until comparatively recent times the growth of plants and animals, and hence the productivity of agriculture, was limited by a lack of phosphorus since only small amounts are released annually from rocks and soil minerals by weathering. As farmers began to use fertilizers in the 19th century, levels of plant available phosphorus in many soils were still very low. This meant that there was little response to other nutrients, especially nitrogen, until phosphorus was applied, i.e. phosphorus was the limiting nutrient to crop growth. This is well illustrated by results from an experiment started in 1899 on a phosphorus deficient soil in Suffolk, England. Table 1 shows that when only nitrogen was applied the yields of winter wheat, spring barley, and mangold roots were only a little better than on the unmanured soil. Giving both nitrogen and phosphorus, however, increased the yield significantly.

TABLE 1 EFFECT OF PHOSPHORUS ON CROP YIELD

Crop and period	Nutrient applied		
	None	Nitrogen	Nitrogen plus Phosphorus
	Yield, t/ha		
Winter wheat* grain 1900 – 1919	1.56	1.83	2.25
Spring barley* grain 1900 – 1919	1.29	1.69	2.10
Mangold roots 1906 – 1919	15.60	17.60	40.40

** In period 1900-1919 around 2.5 t/ha cereal grain would have been considered a good yield.*

TABLE 2 INCREASES IN YIELD OF WINTER WHEAT AND PHOSPHORUS REMOVAL BETWEEN 1852 AND 1992

Period	Yield grain t/ha	Phosphorus offtake in grain plus straw, kg P_2O_5/ha
1852 – 1871	2.70	25
1966 – 1967	3.07	34
1970 – 1975	5.48	50
1991 – 1992	8.69	71

By the 1930s, the average amount of nitrogen and phosphorus applied to arable land in Holland, Belgium, Germany, Denmark, Great Britain and France was 29 kg N and 43 kg P_2O_5 per ha respectively, a ratio of 0.67:1. In the late 1990s, such had been the increase in the use of nitrogen that the ratio was 3.05:1, i.e. 119 kg N and 39 kg P_2O_5 per ha for average use on arable land of these two nutrients in these six countries.

As yields have increased, the total of the nutrients removed with the harvested produce has also increased. This can be seen from data relating to the Broadbalk experiment at Rothamsted in the UK. Winter wheat has been grown in this experiment each year since 1843. Table 2 shows how yield has increased over time and, in consequence, the offtake of phosphorus in grain plus straw has also increased. The same is true for all other crops and nutrients. If the productive capacity of soil, i.e. its fertility, is not to decline, the increased offtake of each nutrient such as phosphorus must be matched by corresponding inputs in fertilizers and manures.

Box 6

History of plant nutrition

Until some 300 years ago, the recycling of the nutrients in the excreta of human beings and their animals was a haphazard affair in most parts of the world. Only the Chinese recycled much of the plant nutrients in the food consumed by the urban population. This, in part helped maintain the productivity of Chinese agriculture, which, in turn, supported the continuation of the Chinese civilisation over many millennia.

The modern fertiliser industry is little more than 150 years old and was first envisaged by the German chemist J. von Liebig. He set down his principles of plant nutrition and production in "Chemistry in Its Application to Agriculture and Physiology", where he stressed the value of mineral elements derived from the soil in plant nutrition and the necessity of replacing those elements to maintain soil fertility. Liebig also propagated the "Law of the Minimum", conceived by Sprengel, a compatriot of Liebig, at the beginning of the 19th century. In essence this states that improving conditions for plant growth by altering one factor can be without effect if another growth factor is limiting (see also Table 1).

In the early years of the 19th century, ammonium sulphate, a by-product from making town gas from coal, and sodium nitrate, from natural deposits in Chile, were available commercially, as were the salts of potassium derived from wood ash. In 1842, J. B. Lawes of Rothamsted, UK, took out a patent for manufacturing superphosphate from bones and mined phosphorus containing rock, and by 1843 was producing superphosphate commercially at a factory in London. So, all three major plant nutrients, nitrogen, phosphorus and potassium were available as chemical salts to supplement the supplies in the soil itself and those applied to the soil in farmyard manure.

Lawes' Works, Deptford—1843.

Phosphorus containing fertilizers in agriculture

Today there is a range of phosphatic fertilizers available to farmers. Some contain only phosphorus, others contain two or more nutrients. Manufacturers often produce a variety of such fertilizers which contain nitrogen, phosphorus and potassium in various proportions. The proportions are adjusted to meet the needs of a specific crop and to allow for the level of plant available nutrients in the soil.

Box 7

Content of P_2O_5 in some common phosphate fertilizers

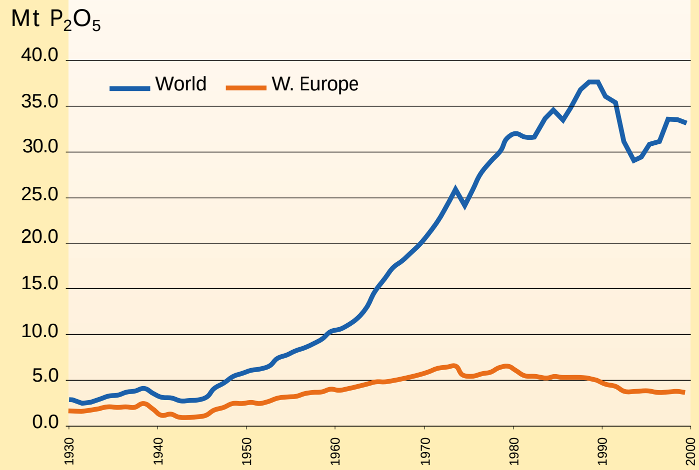
Mono-ammonium phosphate	52%
Di-ammonium phosphate	46%
Triple superphosphate	46%
Single superphosphate	18-20%

The phosphorus in mineral fertilizers such as superphosphate is referred to as inorganic phosphorus. This is to distinguish it from the phosphorus in the complex organic molecules found in living tissues and animal excreta, which is known as organic phosphorus. Farmyard manure is classed as an organic manure but 60 to 80% of the phosphorus it contains is, in fact, inorganic phosphorus.

Consumption of phosphorus fertilizers

In West Europe, phosphate fertilizer consumption peaked in the early 1970s and since 1973 consumption has declined by 50%, or approximately 2% per year. It is now around 3.5 million tonnes (Mt) P_2O_5 annually. Each year, on average, West European agriculture currently applies 43 kg P_2O_5 contained in mineral fertilizer for each hectare of arable land. While the average application to the utilised agricultural area (UAA), which

COMPARISON OF WORLD AND WEST EUROPEAN PHOSPHATE CONSUMPTION 1930-1999



Source: International Fertilizer Industry Association, Paris.

includes grassland and permanent crops, is less, around 27 kg P_2O_5/ha. On most European soils repeated applications of phosphorus in fertilizers have increased the readily available soil reserves. Therefore, at present, the phosphorus status of the soils in many European countries is at a satisfactory level. When there is adequate soil phosphorus, the level can be maintained by keeping the phosphorus balance (phosphorus applied minus phosphorus removed) just positive.

Box 8

Average application rates of phosphorus contained in mineral fertilisers to all crops in European countries on arable land and on utilised agricultural area in kg P_2O_5 per ha, 1999/2000 estimate.

	Arable	UAA
Austria	37	17
Belgium/Luxembourg	31	31
Denmark	20	19
Finland	29	27
France	49	35
Germany	33	24
Greece	39	16
Ireland	78	26
Italy	50	30
Netherlands	45	34
Norway	34	31
Portugal	50	18
Spain	48	27
Sweden	20	19
Switzerland	55	23
United Kingdom	52	23

Source: EFMA

In the interpretation of these data soil fertility, crop rotation, production levels, supply of organic manure and many other factors have to be taken into account.

Box 9

Phosphorus balance in West European agriculture

The national phosphorus balance in Western European countries varies significantly due to differences in the use of mineral fertilizers and manure due to different husbandry practices. Based on the application of mineral fertilizers and the amount of phosphorus removed by crops, only a few countries exceed an average net annual accumulation of 10 kg P_2O_5/ha on arable land and the accumulation rarely exceeds 20 kg P_2O_5/ha. However, when the quantities of phosphorus contained in animal manure are also considered, the positive balance for some West European countries is substantial, particularly in the Netherlands where it exceeds 90 kg P_2O_5/ha each year. For the majority of West European countries, the positive phosphorus balance where manure is included ranges from 20 to 40 kg P_2O_5/ha annually, with a few exceptions where it is well below 20 kg P_2O_5/ha.

Source: Phosphorus Loss from Soil to Water

Using phosphorus more efficiently

Improved recycling to agricultural land of the phosphorus in wastes from urban areas and refuse from animal production would help to close the nutrient loop in the soil-crop-animal-human-soil cycle. There are problems, however, with recycling and recovery.

(1) Consumers must be satisfied that there are no hygiene problems when sewage sludge from urban areas is applied to land where food crops are being grown. There must

also be no contaminants in the sludge which might jeopardise future soil productivity.

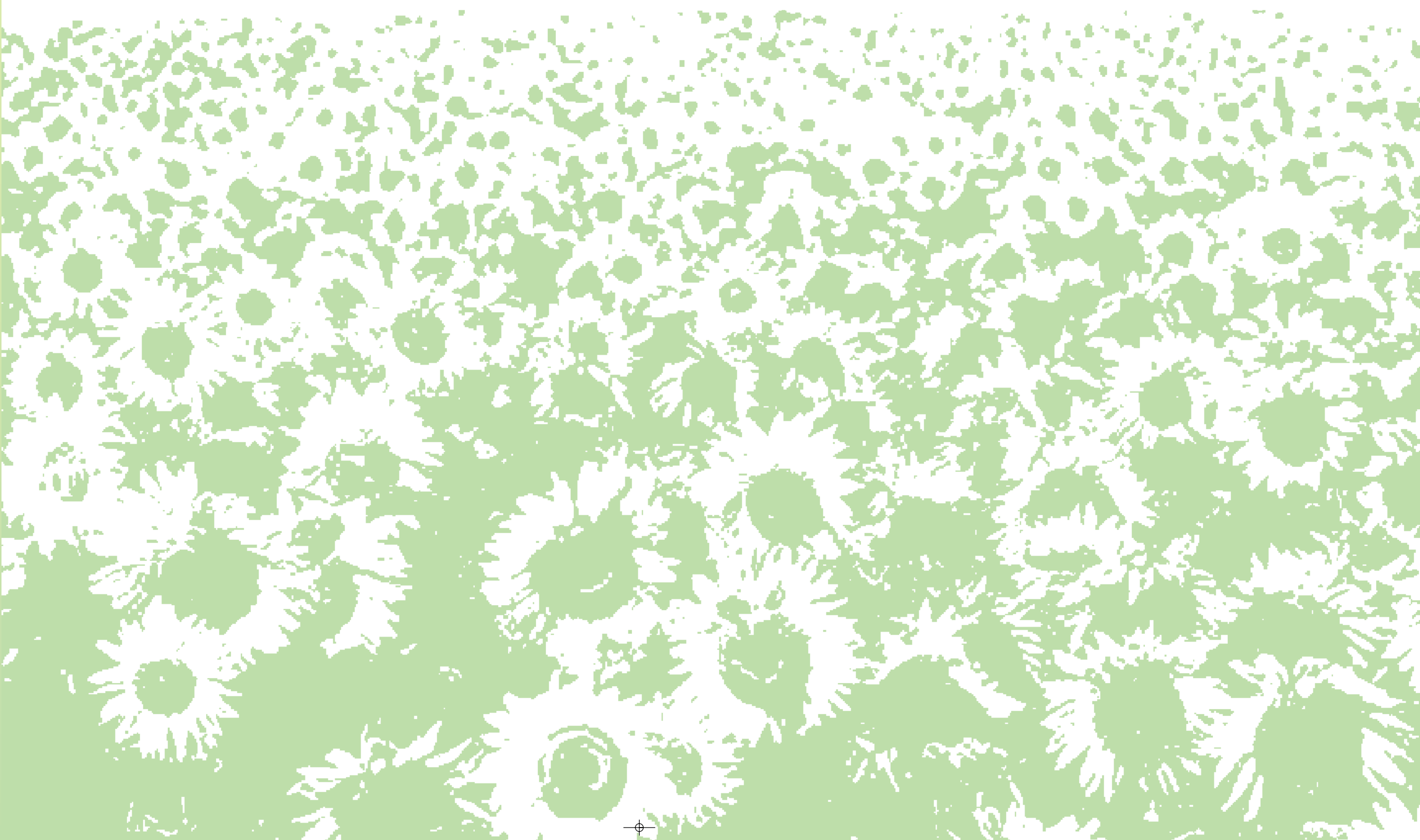
(2) Many farms in Europe now tend to focus either on rearing livestock or growing arable crops. In several regions in Europe there are many farms which produce livestock on an intensive scale but do not have enough land on which they can use the nutrients in the manure to maximum effect.

(3) Animal manure and sludges contain small concentrations of nutrients. Transporting them, especially over long distances, might cost more than the nutrients are worth. Transport also puts other less obvious burdens on the social infrastructure, such as additional road traffic and other related environmental problems. Tonne for tonne, there are many more kilogrammes of phosphorus in mineral fertilizer than in farmyard manure or sludge, making mineral fertilizer more cost effective to transport.

Box 10

The potential for recycling phosphorus for agricultural use

There are two main sources of phosphorus which can be considered for recycling, sewage and animal manures. The phosphate contained in sewage in West Europe is estimated to amount to a maximum of 1 Mt P_2O_5 per year. This phosphate comes mainly from the food we eat, but also from dishwashing and washing detergents and, to a certain extent, industrial effluents. Animals are thought to excrete a similar total amount of nutrient ($N+P_2O_5+K_2O$) to that used in the form of mineral fertilizers each year. However, the ratio of $N:P_2O_5:K_2O$ in excreta is different from that in mineral fertilizers, with more phosphorus and potassium in relation to nitrogen. The intensification of livestock production in some countries has led to an increased import of phosphorus in feeding stuffs, which represents a very significant addition to West Europe's phosphorus balance. Disposal of animal manure in the high density livestock areas has contributed to the problem of excess phosphorus in soil. The amount of phosphorus excreted by livestock in West Europe could be some 50% higher than the amount currently applied as mineral fertilizer. However, the quantity of the phosphorus excreted by livestock that can be recycled is limited, because it can only be collected while the animals are housed.



Phosphorus and soil

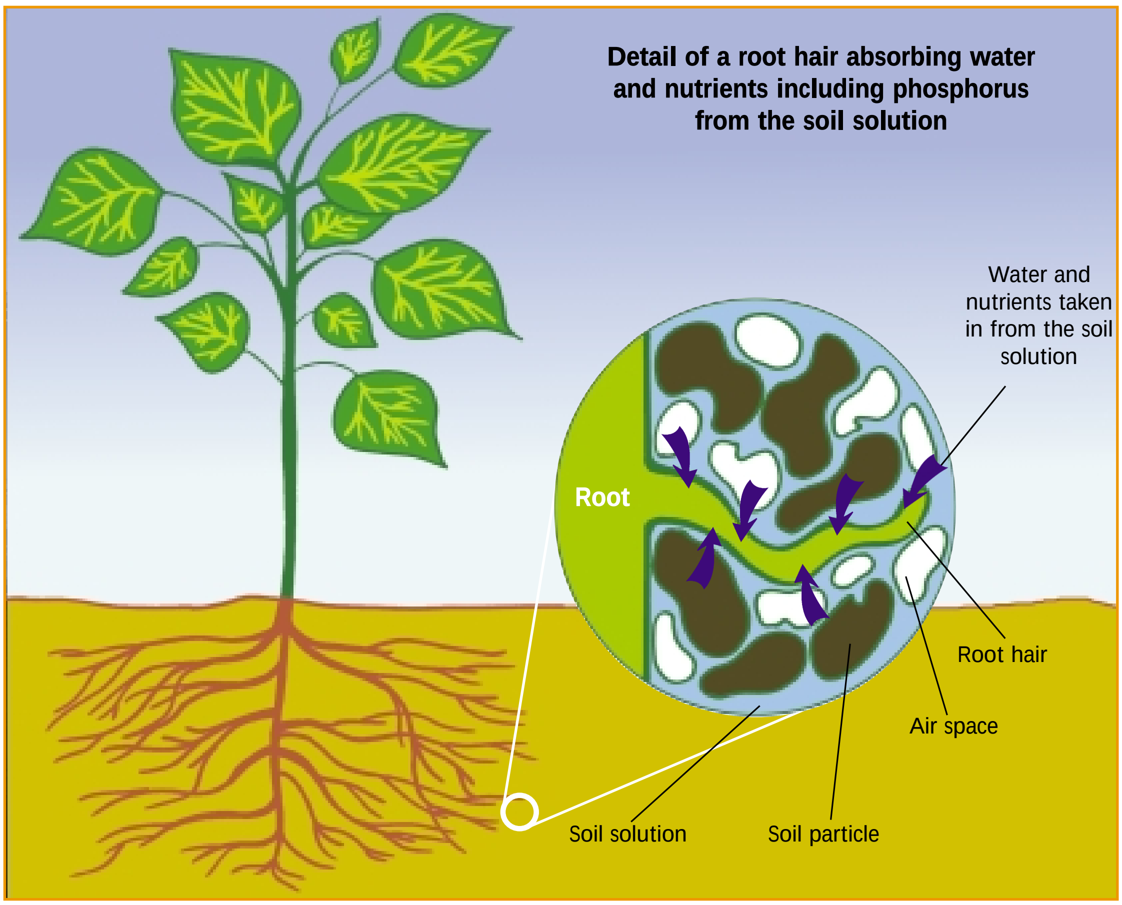
Plant nutrition, soil texture and plant root systems

It is helpful to know something of the relationship between plant nutrition, soil texture, root growth, and the availability of nutrients in the soil in order to understand how it might be possible to increase the efficient use of phosphorus in agriculture.

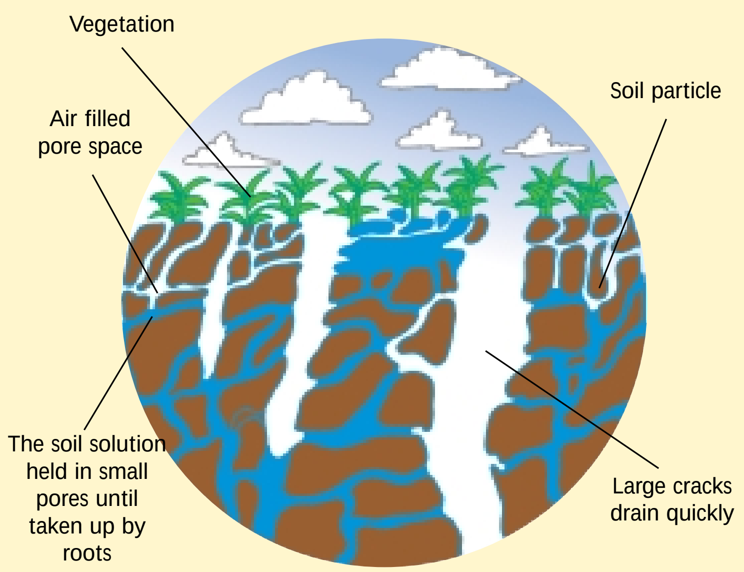
Plant nutrition

In human nutrition the focus is on proteins, starch, sugar, fibre and vitamins, all products manufactured for us by plants or from plants via animals. Plant nutrition, however, is considered in terms of the individual elements required by the plant. These include nitrogen, phosphorus, potassium, carbon, sulphur,

© MAFF. Crown copyright. A well-structured soil (left and middle) allows roots to grow freely. A poorly-structured soil (right) prevents root growth.

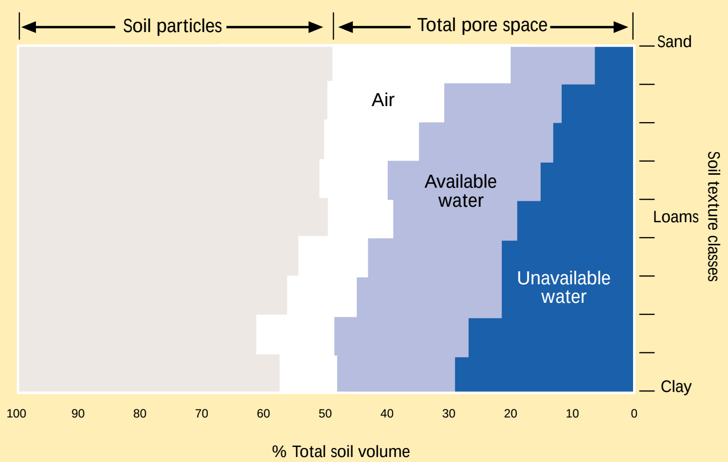


hydrogen and many others. Plant roots take up all nutrients from the aqueous solution in the soil apart from carbon, hydrogen and oxygen, which are acquired from carbon dioxide in the air via the leaves and the water in the soil.



The soil solution which contains plant nutrients, occupies only a portion of the total pore space between the solid particles. An important feature is the variation in the cross-sectional size of the pores. Water added to soil in rainfall, drains rapidly down larger cracks under the influence of gravity but is retained for longer in the larger pores. In the smallest pores, the soil solution is retained by surface tension until the water is taken up by plant roots. Drainage water carries water soluble substances with it, a process called leaching. Water moving rapidly down large cracks can also carry small solid particles with it. These particles can be eroded from the soil surface, or from the sides of the cracks.

Relation between solid particles and pore space in soils of different texture



Physical properties and texture of soil

Soils are identified as heavy (clayey), loamy and light (sandy). This relates to the proportion of the mineral particles of clay, silt, fine sand and sand which are partly responsible for the overall texture of each soil. In addition, there is soil organic matter which mostly consists of organic material broken down by earthworms and the population of microscopic microbes which inhabit the soil.

In many soils the mineral particles can be held together by various mechanisms to form crumbs. Within the crumbs and between them are spaces (pores) which hold air and water, both of which are essential to the plant. It is important that the pores form interconnecting passageways from the surface deep down into the soil to allow the movement of air and the removal of excess water.

Plant root systems

Plants frequently have large root systems, a feature perhaps that relates to the time when they had to acquire sufficient nutrients from

Plant roots proliferate in zones of the soil which are enriched with phosphorus (left) compared to soil without phosphorus enrichment (right). (Adapted from Drew and Saker, 1978) soils which were nutrient poor. For example, a good crop of winter wheat could yield 10 t/ha of grain. The root system associated with this crop will weigh about 1.5 t/ha dry weight but extend to 300,000 km/ha or about 100 m of root for each plant which is only about 1 m tall above ground. Roots grow along the passageways in the soil, but the root tip of cereal plants, for example, can only enter pores larger than about 50 µm (0.05 mm) in diameter. Thus roots do not grow in compacted soil and so cannot take up the nutrients it contains.

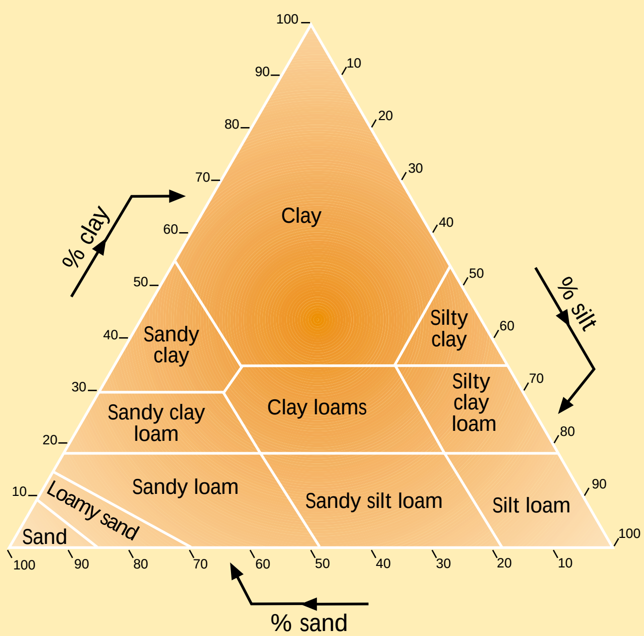
Well structured soils have interconnecting pores of many different sizes containing both air and soil solution. Since plant roots cannot enter the smaller pores, the nutrients have to move towards the root. As the root takes up nutrients from the soil solution, the concentration decreases and, to redress the balance, nutrients move in the soil solution towards the root by a process known as diffusion.

Soil phosphorus and its availability

The chemistry of phosphorus in the soil is complex because the phosphorus is associated with many different compounds to which it is bound with a range of bonding energies or strengths.

When phosphatic fertilizers are added to soil, only a fraction of the phosphorus is taken up immediately by the plant root. The remainder becomes adsorbed (attached to the surface) to soil particles. Where the attachment is weak, the phosphorus can transfer back into the soil solution. After the initial adsorption, further reactions lead to absorption (assimilation), which means that the bond is stronger and the

Definition of soil type



Box 11

The nutrient requirement of plants

Plants live, grow and reproduce by taking carbon dioxide from the air, energy from the sun, and water and mineral substances from the soil. Plants contain practically all (92) of the elements known to occur in nature, but only 16 are needed for good growth and, of these, 13 are absolutely essential. These mineral nutrients are often classified as either major plant nutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) because they are required in large amounts, or "micro nutrients" (boron, chlorine, copper, iron, manganese, molybdenum and zinc) which are only required in trace amounts. Soils to which plant nutrients have never been added will invariably be unable to supply enough nutrients to produce optimum yields. To make good this deficiency, fertilizers and manures will need to be added, because healthy plants, like humans and animals, require a balanced nutrition.

phosphorus becomes less readily available. The speed of these reactions and therefore the speed at which a deficiency in phosphorus becomes apparent depends very much on the type and size of the mineral particles, the presence of other elements such as aluminium, iron and calcium, soil acidity and organic matter.

Organic phosphorus in soil can be associated either with soil organic matter (humus) or recently added organic debris coming from plants or animals. These organic molecules cannot be used directly by plants. They have to be broken down by soil microbes to release inorganic phosphate ions which can be taken up by plant roots or enter into the same reactions as other fertilizer phosphate ions.

Phosphorus in the soil solution is either taken up by plant roots or goes into a readily available pool where it is held weakly. From there, it moves to a less readily available pool where it is held more strongly (Fig. 1).

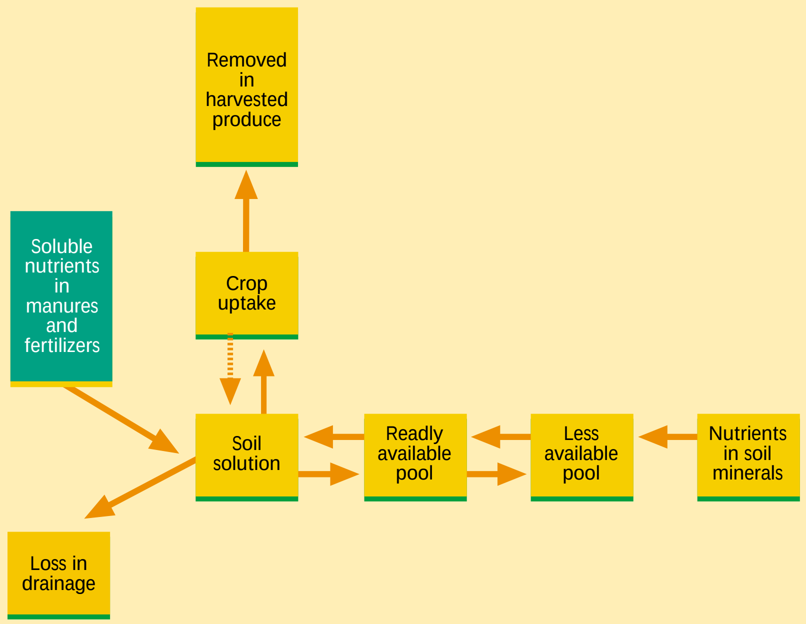
Soil phosphorus reserves

Past concepts about the behaviour of phosphorus in soil suggested that phosphorus added in fertilizers reacted with other soil constituents and became permanently fixed in soil and therefore unavailable to future crops. It is now known that this is not always the case for many soils. When phosphorus is added to the soil it becomes associated with various soil elements. Although only a small proportion of the phosphorus in each application of fertilizer is held weakly, the amount increases as the number of fertilizer applications increase. This explains why the availability of phosphorus has actually increased in soils which have been cultivated and fertilized over many years.

The value of soil phosphorus reserves

Enriching soil with readily available phosphorus reserves benefits crop yields, making them invariably larger than those achieved on similar soils without such reserves. Even when large

FIGURE 1. SCHEMATIC REPRESENTATION OF THE P-CYCLE IN THE SOIL-PLANT SYSTEM



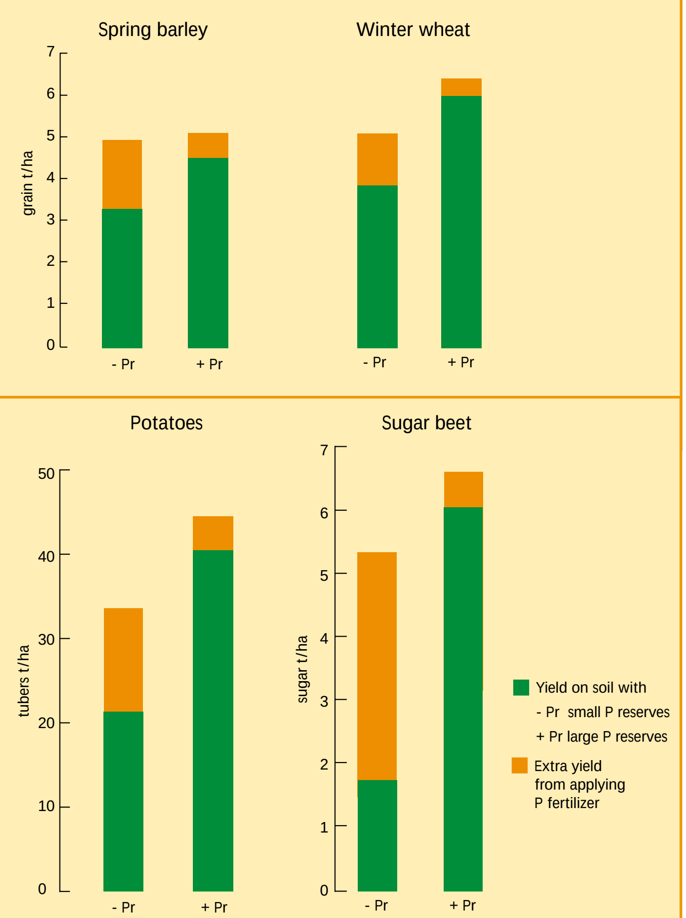
amounts of phosphatic fertilizer are applied to soil with little readily available phosphorus, yields are not always increased in the short term to equal those on the enriched soil. This is because, on fertilized soils, readily available phosphorus reserves are uniformly distributed throughout the volume of top soil exploited by roots. Thus phosphorus in the soil solution is replenished quickly wherever it is depleted by root uptake. On soils with different levels of reserves, it is important to assess the level of readily available phosphorus reserves in the soil and then adjust the amount of phosphatic fertilizer that needs to be applied in relation to these reserves. This can only be done through field experiments and by appropriate methods of soil analysis.

Analysing soil for readily available phosphorus

For agriculturalists, it is useful to know the quantity of phosphorus in the soil solution and in the readily available pool (Fig. 1). Phosphorus is extracted with a suitable reagent from a representative soil sample for analysis. The amount of phosphorus extracted will give an indication of how the crops will respond to a fresh application of phosphatic fertilizer; high, medium or low responsiveness. The yield of a crop grown on a "highly responsive" soil, for example, will be greatly increased by applying phosphorus. On other soils, the increase in yield will be less, and there may be no increase in yield on soils with substantial readily available phosphorus reserves.

The phosphorus status of European soils is estimated by routine analysis and for many countries some 25% (5-55%) of soils test as very low and low in readily available phosphorus. Such soils require significantly more phosphorus to be applied than is

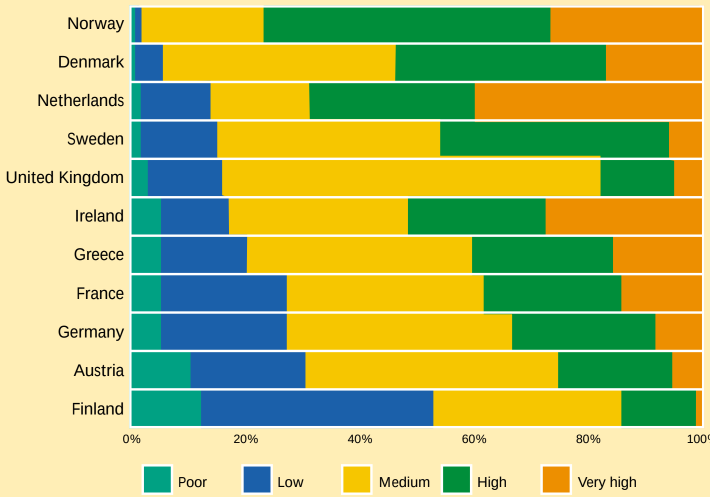
Effect of adequate P reserves on the yields of four arable crops



Source: Johnston et al. 1986

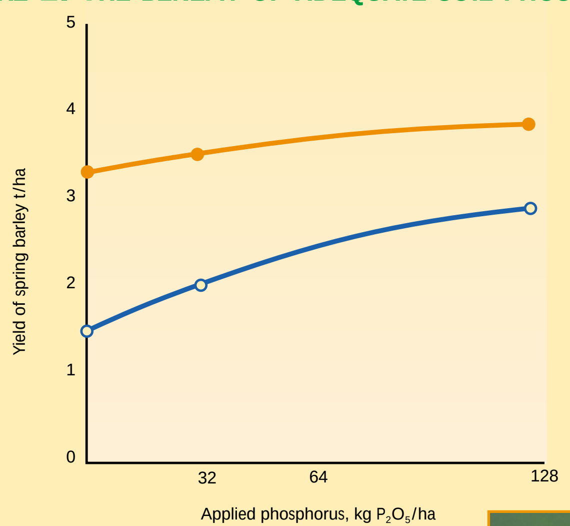
removed by the crop to increase soil reserves and thus soil fertility. For many countries some 40% (15-70%) of soils test as high and very high in readily available phosphorus. On such soils, when crops are grown that have small, inefficient root systems but a large daily intake of phosphorus at critical growth stages, it may be necessary to apply more phosphorus. On soils with a medium phosphorus analysis value, applications need to sustain the phosphorus status. This may require a small extra amount of phosphorus over and above that removed in the harvested produce of the crop.

ESTIMATED NATIONAL PHOSPHORUS STATUS OF EUROPEAN SOILS



Source: Phosphorus Loss from Soil to Water

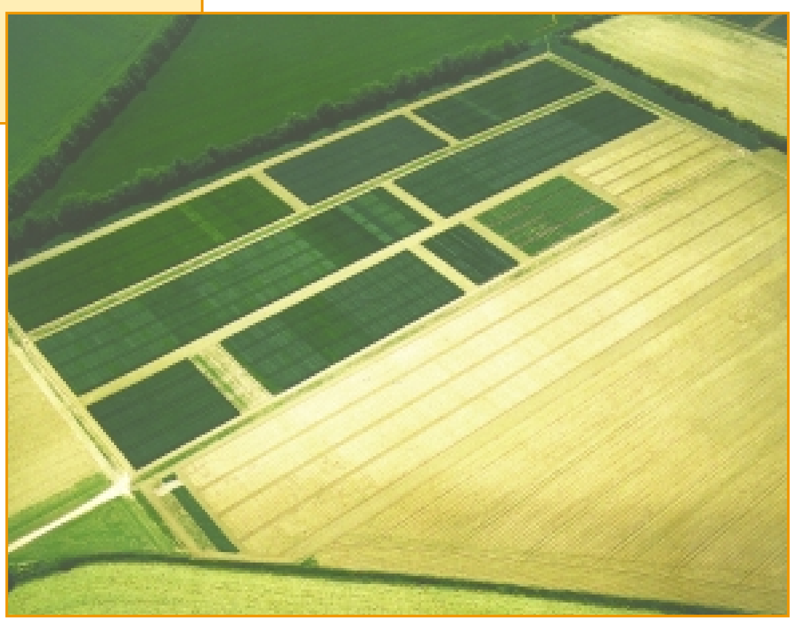
FIGURE 2. THE BENEFIT OF ADEQUATE SOIL PHOSPHORUS



Response of spring barley to a freshly applied P on a soil with adequate (orange line) and low (blue line) phosphorus status.

Fertilizer recommendations

The efficiency with which plant nutrients are used has been a concern of soil chemists and agronomists for a long time. Fertilizer recommendations are developed from the results of field experiments. In such experiments, increasing amounts of phosphorus are applied to plots which also receive adequate amounts of all other nutrients. The optimum application can be determined from response curves which relate the crop yields to the different amounts of phosphorus applied. An example is shown in Fig. 2. Field experiments, however, are too expensive to be carried out on all the crops grown in different farming systems and on all soil types. Therefore, once the amount of phosphorus needed to achieve optimum yield is identified, it will be considered appropriate for all other soils of the same type. In this way, reliable fertilizer recommendations can be established from a limited number of field experiments.



Arial photograph of a field experiment (photo: SKW Piesteritz)

Desirable soil phosphorus levels and critical values for readily available soil reserves

As readily available phosphorus increases, so does yield, rapidly at first, then more slowly, levelling off as it approaches the yield plateau. The level of phosphorus required to produce yields close to the plateau can be considered as the critical value for that soil and crop (Fig.3A). Figure 3B shows examples from an experiment at IACR Rothamsted.

Below the critical level, yield is appreciably less than it could be, and can therefore represent a financial loss to the farmer. For soils much above the critical value there is so little increase in yield that there is no financial justification for the farmer to apply more fertilizer. So the rationale for phosphorus application is to maintain soils just above the critical value. This can be done by replacing the quantity of phosphorus that is removed from the field in the harvested crop (maintenance or replacement application). This concept is becoming well established among farmers and their advisors, who check that the appropriate soil level is being maintained simply by analysing a sample of soil every four or five years.

This approach is particularly appropriate to phosphorus, because only a small proportion, perhaps 15-20% of the total amount of phosphorus in the plant comes directly from the fertilizer applied to that crop. The remainder must come from soil reserves. These reserves will be seriously depleted if they are not replaced. Allowing soil reserves of readily available phosphorus to fall below the critical value can result in a serious loss of yield.

Photo: Kemira

FIGURE 3A. SCHEMATIC RELATIONSHIP BETWEEN YIELD AND READILY AVAILABLE SOIL P

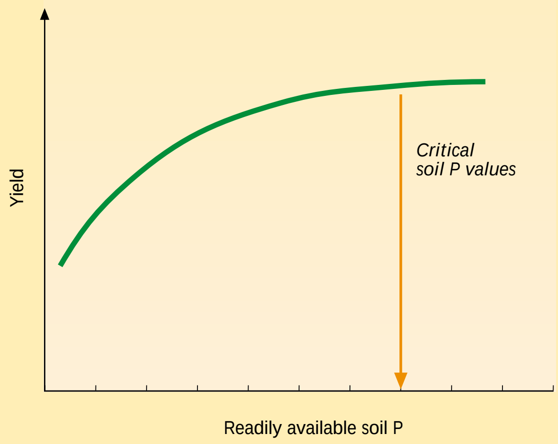
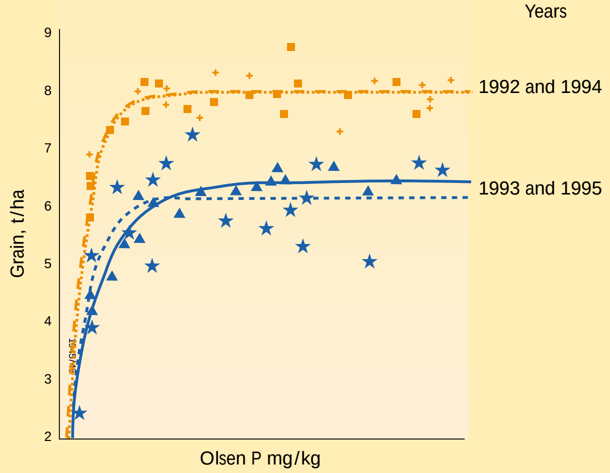


FIGURE 3B. YIELD OF WINTER WHEAT RELATED TO OLSEN P IN SOIL*



Source: IACR Rothamsted Experimental Station

* Readily available soil P reserves can be measured by extracting the soil with different chemical reagents, including sodium bicarbonate (Olsen's method, Olsen P).

Box 12

Crop removal of phosphorus in average yields of harvested produce in Western Europe, 1999 estimate.

	Yield t/ha	Concentration kg P_2O_5/t	Offtake, kg P_2O_5/ha
Oilseed Rape	3.05	16.7	51
Pulses	3.07	9.8	30
Wheat	5.95	7.8	46
Potatoes	33.7	1.1	37
Sugar beet	55.8	0.8	45

Box 13

The topsoil and its phosphorus content

The topsoil is often identified as the plough layer, i.e. the 20-30 cm depth of soil which is turned over before seedbed preparation. The crop takes up the majority of the nutrients it requires from the topsoil. The volume of a hectare of topsoil is around 2,500 m^3 and weighs approximately 2,000 tonnes. The topsoil can contain between 3 and 7 t P_2O_5 per ha. However, only a minute fraction (0.02 to 0.10%) of this total phosphorus will be present in the soil solution at any one time. A larger proportion, perhaps 0.5 to 10%, will be in the readily available pool, capable of releasing phosphorus to the soil solution. Between 25% and 50% of the soil phosphorus may be present as organic phosphorus, mainly within complex molecules in soil organic matter. The organically bound phosphorus mineralises, i.e. becomes available through the activity of soil microbes, but only slowly. Approximately 1% to 3% of the organic phosphorus becomes available to crops each year. In temperate areas this could amount to some 5 to 40 kg P_2O_5/ha, but the smaller amounts may not meet the requirements of the crop. The amount of phosphorus mineralised shows great variability and is very dependent not only on climatic conditions but also on the farming system. In general, more phosphorus mineralises in grassland and pasture soils than in arable soils.

Phosphorus and the Environment

Phosphorus and some environmental issues

Some 25 years ago, reports of undesirable changes in the freshwater environment in some countries led to a growing concern for the aquatic environment in general. These changes were considered to be related to the increasing concentration of nutrients in the water.

Box 14

Sources of phosphorus to waters in Europe, % contribution

Point sources (urban contribution)	50-75%
Agriculture	20-40%
Natural loading	5-15%

Source: Nutrients in European Ecosystems

Nutrients are fundamental for plant growth in all ecosystems, as much in water as on land. The natural nutrient status of a water body such as a lake depends on its size, depth, geology, retention time and the use of land in its catchment area. Some soils release more salts and nutrients than others and therefore different water bodies in their natural state can be at different trophic, i.e. nutrient concentration, levels. An increase in available nutrients or nutrient enrichment of a water body is called eutrophication (from the Greek word eutrophos, meaning nourishing, well nourished, providing good nourishment). However, this term has become associated with adverse water quality and is now frequently used to describe the negative consequences of nutrient enrichment.

Nitrogen, phosphorus, carbon and, in some cases, silicon are the nutrients of most concern in relation to eutrophication. However, because phosphorus is the most limiting nutrient in the fresh water environment, it attracts the most attention when the problem of eutrophication is considered in relation to fresh water.

Lakes, and shallow lakes in particular, are aquatic ecosystems often with an ecological structure which consists of a great diversity of plant and animal life. This structure is finely balanced and the species are inter-dependent. Birds and mammals rely for their food supply not only on the total productivity of the species living in the lake but on the presence of particular species, which in turn is subject to the availability of nutrients. The microscopic algal communities, phytoplankton, are the first link in the food chain for aquatic animals and fish. These and other floating plants acquire their nutrients directly from the water, whereas the macrophytes that root into the lake bottom can obtain nutrients from the sediments. These larger plants are crucial for the maintenance of the oxygen level in the water.

Frequently, an early symptom of change in the ecological structure is a rapid increase in the

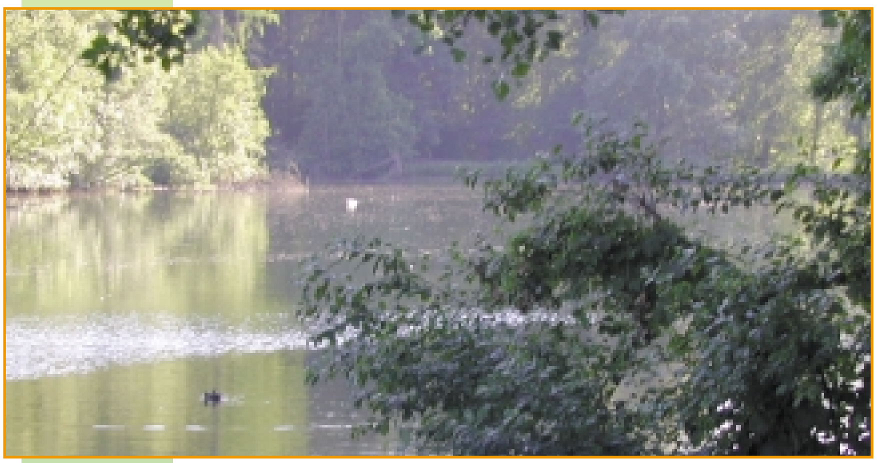
Developing algal bloom

Box 15

Trophic levels of phosphorus in fresh water, total P concentration mg P/l (annual average)

Ultraoligotrophic	<4
Oligotrophic	4-10
Mesotrophic	10-35
Eutrophic	35-100
Hypereutrophic	>100

Source: Nutrients in European Ecosystems



growth of the phytoplankton. Rapid algal growth can create an algal bloom, i.e. a dense mass of algae, near the water surface. Light is prevented from reaching the plants growing on the lake bottom, resulting in a decline in their growth. The cloudy water and the change in plant diversity, and plant death in the worst cases, can have an effect on the variety of fish in the lake.

Like all green plants, algae assimilate carbon dioxide and produce oxygen during daylight, but require oxygen for respiration during the dark periods. When a bloom of some species of algae is developing rapidly, there is a negative net oxygen balance and the deoxygenation of the water may lead to the suffocation of fish and higher animals in the lake. When algae die and settle, they decompose – a process which requires much oxygen. During their decomposition in oxygen-depleted water, toxins may build up. Also, during certain conditions, toxic algae may develop and the toxins they produce can affect fish stocks. Moreover, animals drinking the water can become ill and even die.

The sources of water and nutrients in inland waters

The transfer of nutrients to water is largely the result of natural processes, which are accelerated by agriculture, including intensive animal husbandry, and by direct anthropogenic discharges. In general, the load of phosphorus increases in relation to the level of human activity and according to population size and land management. With no human activity, it is estimated that phosphorus levels in water would only be 5-10% of current amounts. Initially, most phosphorus additions to inland surface waters were attributed to discharges from point sources, especially municipal sewage treatment works and industrial effluent. The contribution from diffuse sources, including agriculture, was considered to be insignificant. However, as the amount of phosphorus lost from point sources has declined, the proportion of the total phosphorus load coming from agriculture has increased.

Water reaches lakes directly via rainfall and by rivers which are fed by three routes.

(1) Water passing over the land surface, i.e. surface runoff.

(2) Piped drainage systems installed on farmed land to remove excess water quickly especially water which moves through the soil profile by preferential flow.

(3) Springs and streams. On naturally drained land water seeps vertically through the soil until it meets an impermeable layer, it then moves sideways until it discharges as a spring.

The amount and quality of the water reaching a fresh water body, including its nutrient content, depends on many criteria such as rainfall, hydrology, geology, topography and land use.

Nutrients can be lost from land to water in various ways.

(1) In eroded soil which forms the lake bottom sediment and can release nutrients to water.

(2) In surface runoff which can carry fine particles of soil, organic material and nutrients in solution.

(3) In water which, while percolating through the soil to drains or springs, has dissolved soluble nutrients from the soil.

(4) In water from municipalities, industries and storm water discharged into sewers.

The productivity of a fresh water body, in terms of the growth of plants and animals, is often controlled by the availability of

phosphorus. When the problems associated with eutrophication were first related to the concentration of phosphorus in the water, the source of the phosphorus was considered to be effluent from sewage treatment works and industries. Such outflow contained soluble inorganic phosphorus compounds from detergents and other sources, and the microbially decomposed organic phosphorus in residues from the preparation of food and in human sewage. To limit such losses to water the larger sewage treatment works were required to remove the phosphorus from the effluent before discharge (EU Urban Waste Water Treatment Directive 91/271/EEC).

In practice, the implementation of this requirement in Europe was slow and smaller treatment works were not included in the scope of the directive. In many cases, it became clear that simply limiting the removal of phosphorus from these discharges did not always have the desired effect of restoring the biological balance within affected inland waters. As a result, attention has tended to focus on the losses of phosphorus from agriculture, although smaller treatment works, and those where the phosphorus removal is substandard, may still be responsible to some extent.

Box 16

Erosion

Rainfall can be heavy or light and the term "storm" is often used to describe a focused period of rainfall of high intensity. Storms are classically described by the Beaufort Scale in relation to wind speed. In Europe any rainfall greater than, or equal to 7.5 mm per day may be considered significant enough to cause erosion, whereas 5 mm per hour is a convenient measure of high intensity rainfall. The duration of rain is also important and it is suggested that anything greater than, or equal to, 2 mm per hour with a duration of 5 hours or more constitutes a significant storm for nutrient transfer.

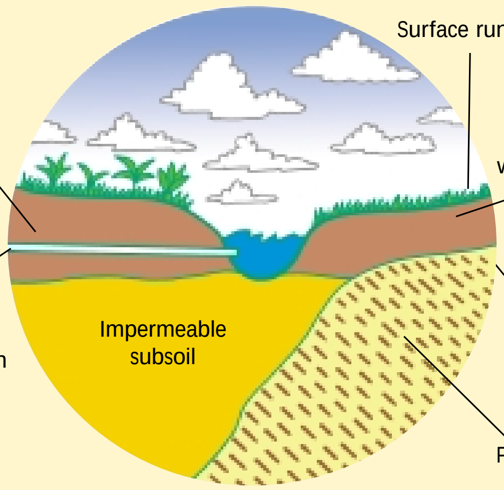
Pathways and fractions of phosphorus loss from agriculture to water

Phosphorus loss from agriculture can come from both point and diffuse sources. Point sources include waste water from farms and dairies and seepage from manure stores. Diffuse sources relate to individual fields from which there can be soil erosion, surface runoff and drainage.

Soil erosion can be caused by wind and rainfall when either detaches mineral and organic particles from the body of the soil. Wind erosion is a feature of mainly fine textured and organic soils, whereas water erosion can occur on many soil types. Both can transport soil to rivers and lakes which can become enriched by nutrients associated with the particles. Wind and water erosion are more severe when the land is not protected by a permanent cover of vegetation. Water erosion is a particular problem in regions where heavy rain falls on sloping land.

Animal husbandry predominates where topography (sloping, undulating landscapes) and climate (high rainfall) make arable husbandry difficult. Permanent grassland minimises the risk of soil erosion but problems can arise from spreading animal manure and slurry which is produced in the period when the animals are housed. When excessive quantities of slurry and manure are applied to soils and this is followed by heavy rain, surface runoff may occur. Pasture systems can also supply large loads of particulate phosphorus, particularly where there is a large population of livestock. Large numbers of cows grazing limited areas of pasture can destroy the surface vegetation (poaching) which leads to an increased risk of soil erosion. Surface runoff may carry nutrients, including phophorus in inorganic phosphorus compounds and organic matter.

The concentration of phosphorus in water percolating through the soil to drains and springs is usually very small and difficult to detect with accuracy. The amount of phosphorus lost by this route will depend on the volume of drainage and the phosphorus concentration but the amount is generally small. Phosphorus is adsorbed onto soil particles, especially in the top cultivated soil layer. However, cracks and channels may allow some phosphorus to by-pass the soil filter and enter directly into drains. Losses in drainage can be larger from soils over enriched with phosphorus than from soils where the level is just sufficient to give optimum crop yields. This is a good reason why soils with about the critical value for readily available soil phosphorus should not be over enriched. More significant than the total amount of



In periods of heavy rainfall water flows over the soil surface. This water can carry eroded soil particles or organic manures recently applied to the soil. When the rainfall is less intense, it percolates into the soil and the excess leaches downwards carrying soluble substances with it. If the subsurface horizons are permeable, the water continues to move downwards to fill up all the spaces and voids. The water in these aquifers can be extracted by pumping from boreholes to meet the needs of humankind. If the subsurface horizons are impermeable, the drainage water moves laterally through the soil, interflow, until it discharges into ditches, streams and rivers. If the surface soil above an impermeable subsoil is clayey, then artificial drains are often installed to remove water more quickly, improve soil conditions for cultivation and encourage better root growth.

Box 17

The amounts of water soluble phosphorus needed to raise the phosphorus concentration in soil drainage (mm/ha/year) are very small.

	mm drainage/ha/year			
	100	250	500	1000
Concentration of P in water	kg P_2O_5/ha			
35* mg P/L	0.08	0.20	0.40	0.80
100* mg P/L	0.23	0.56	1.12	2.24

* 35 mg P/L is the lower limiting value for eutrophication
* 100 mg P/L is the lower limiting value for hypereutrophication - see Box 15

phosphorus in the aquatic system is that which is bioavailable, i.e. which can be used immediately, and therefore dictates the rate at which algae grow. Most of the phosphorus in solution will be bioavailable, whereas that associated with eroded soil is much less so. Research is therefore increasingly focusing on the bioavailability of phosphorus lost from land to water.

Minimising phosphorus losses from agriculture and lake restoration

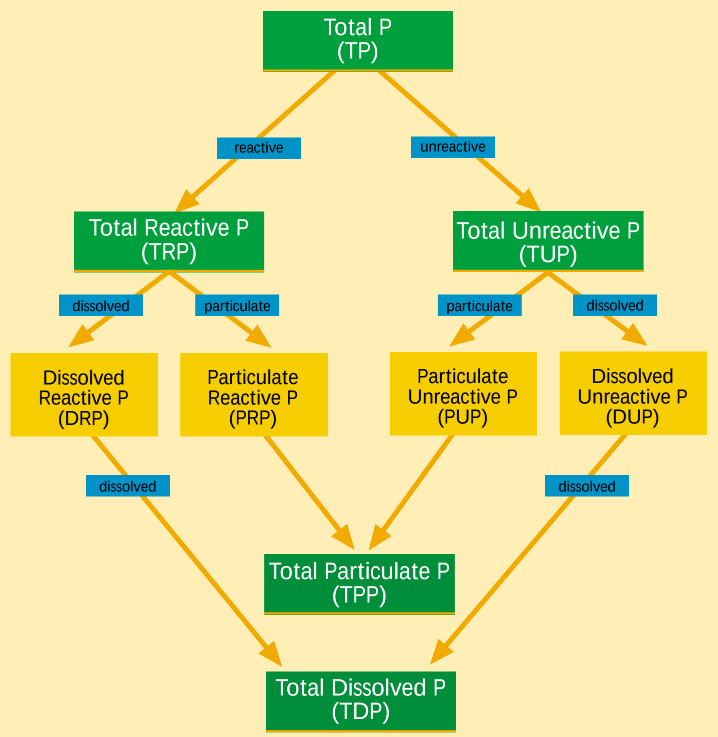
The link between cause and effect is not always as simple as might at first appear. Apart from extreme cases, where losses of phosphorus from agricultural soils are very large, there is no certainty that reducing phosphorus loss will prevent the adverse effects of eutrophication. As more is learned about the complexity of rivers and lakes it has become increasingly difficult to identify simple solutions to these problems.

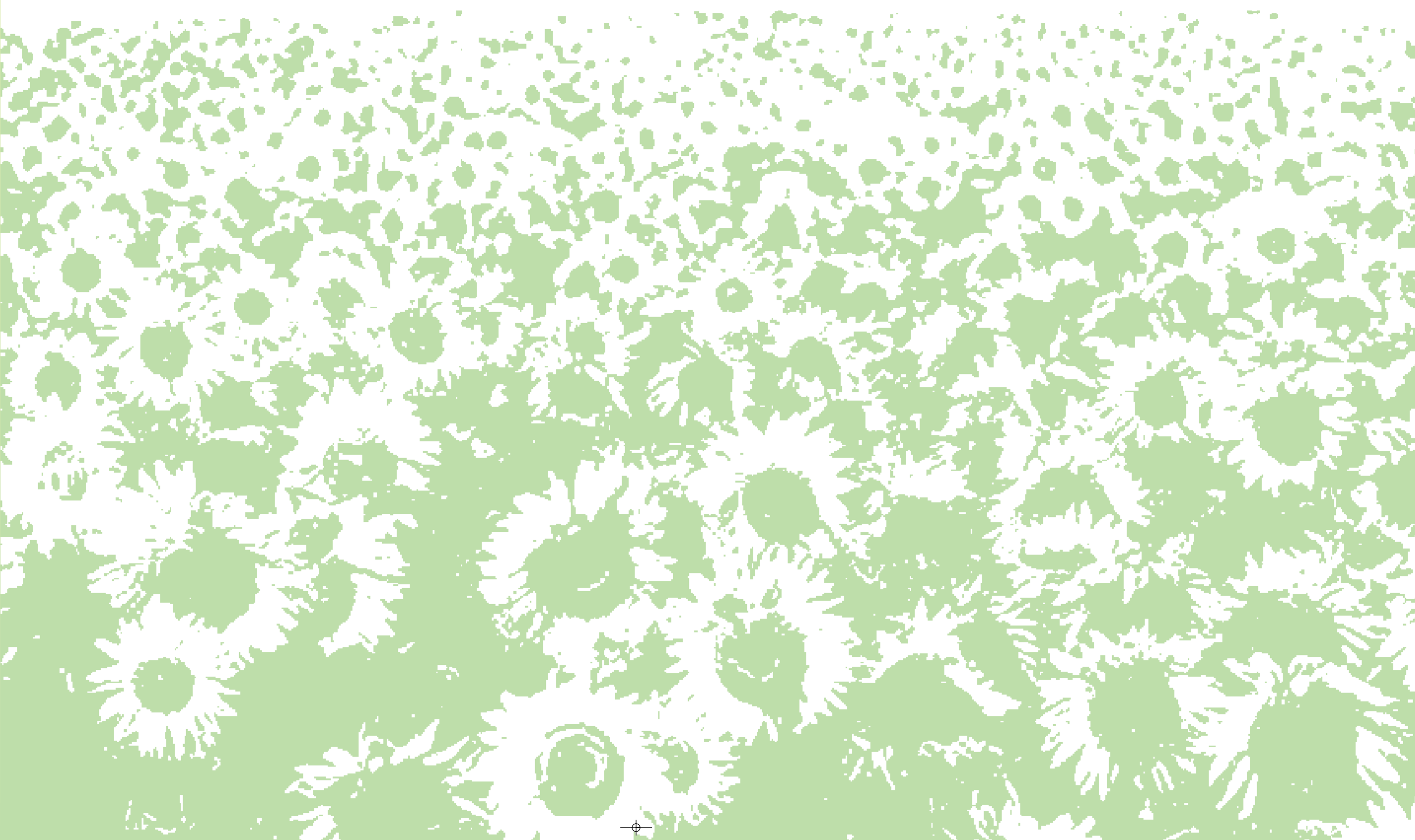
An effective response to eutrophication in large, deep lakes might be different to that for shallow lakes and wetlands. For example, as the amount of bioavailable phosphorus determines the rate of algal growth, it was once thought that reducing the input of phosphorus via rivers would prevent the development of algal blooms in all water bodies. When the major phosphorus load could be attributed to a few readily identified point sources, it was possible to take action to minimise phosphorus loss into rivers. For deep lakes this met with a certain amount of success. Similar benefits, however, have not always been observed for shallow lakes and wetlands.

Shallow lake restoration programmes based only on lowering the concentration of phosphorus in the influx water have tended to be disappointing. Often, excess algal growth has continued, turbid water has not cleared and plant communities have not returned. Possible remedies to prevent eutrophication in shallow lakes have therefore to be reconsidered.

It is not enough to introduce measures simply aimed at decreasing the amount of phosphorus lost from agricultural land to water in the hope of maintaining or rapidly re-establishing the biological balance in shallow lakes and wetlands. Factors other than nutrient inputs must be manipulated if diversity of species is to be restored. This process, which is called biomanipulation, relates to the deliberate alteration of the biological community to achieve a desirable change in the environment. In restoring a lake, for example, this can often involve the selective removal, or introduction, of certain species of fish (Moss et al. 1996).

Forms of P in water





Phosphorus in Agriculture and the Role of the Fertilizer Industry

Phosphorus is an essential nutrient for plants, and in the past, food production was often restricted by its limited availability. Thanks to scientific and technological advancements phosphorus has been available to farmers for some 150 years in easy to apply forms of mineral fertilizers to supplement soil supplies and phosphorus recycled through organic manures. The increased use of mineral fertilizers, including phosphatic fertilizers, has been one factor among many which has helped to assure food security in Europe. Maintaining levels of available phosphorus in the soil-plant-animal system continues to be important to ensure sufficient plant growth and healthy animals.

Changing concepts in the management of phosphorus in agriculture

From the 1950s until the late 1980s European governments promoted agricultural policies which aimed at improving self-sufficiency in agricultural produce. This generally required the improvement of soil fertility and the prevailing recommendations for nutrient inputs were for larger amounts, particularly of phosphorus, than were being removed by the harvested crop. Thus, the status of soil phosphorus as a major contributor to overall soil fertility, or the ability to produce crops, was improved. During this period the introduction of crop varieties with a higher yield potential demanded a corresponding increase in the input of nutrients.

Some 15-20 years ago, environmental concerns related to agriculture started to grow and it became increasingly clear that the nutrient cycles in agriculture, as well as in society in general, had to be tightened to minimise losses of phosphorus from soil to water. As part of this process, farmers have been encouraged to follow published Codes of Good Agricultural Practice in all aspects of husbandry, including the use of fertilizers. The fertilizer industry has strongly advocated best nutrient management practices which seek to optimise yields while minimising any risk of

The response of potatoes to phosphorus on a soil with low P status (zero application in the bottom left hand corner). At harvest the yields of tubers for 0, P1, P2 and P4 were 13, 29, 32 and 33 t/ha respectively. Source: IACR Rothamsted adverse environmental impact. As farmers follow such guidelines they are not only helping to preserve the environment, but they are also benefiting financially.

One approach to minimising phosphorus losses from soil to water is to ensure that soils are not over enriched with phosphorus from mineral fertilizers or manures. The greatest risk of over enrichment is associated with intensive livestock production where animal manure is produced in such large quantities that the supply of nutrients greatly surpasses the needs of crops. The amount of phosphorus in manures could be decreased if the efficiency with which animals utilise the phosphates in their feed could be improved. This could be achieved by adding the enzyme phytase to feed to assist the break down of the otherwise unavailable phosphorus compounds in feeding staffs or by improving the effectiveness of inorganic feed phosphorus supplements.

Integrated plant nutrient management

The concept of integrated plant nutrient management presents another opportunity for improving nutrient cycles, as farmers are encouraged to carefully consider the need for all the nutrient inputs required to optimise crop production. In this way the farmer maximises his financial returns while minimising any adverse effect on the environment. In terms of phosphorus, this concept implies that all available sources should be taken into consideration, including soil phosphorus as well as that contained in applied manures and mineral fertilizers.

Integrated phosphorus management fits well with the idea of maintaining a soil at around the critical level of readily available soil phosphorus. The industry will continue to promote the addition of phosphatic fertilizers to soils where phosphorus is below the critical value. Once the optimum level has been achieved, the industry's advice will be to add just enough phosphorus to replace that which is removed in the produce taken from the field.

Mineral fertilizer consumption, and in particular that of phosphatic fertilizers, has decreased over the past 30 years in Western Europe. The industry forecasts that this trend will continue. This may have a downside, since soil fertility

and crop quality could be put at risk. As an example, restrictions on fertilizer use which result in suboptimal applications of nutrients could mean that crops do not reach the appropriate quality standards, preventing farmers from selling their produce in external markets. Or, as is the case in some West European countries, the application of too little phosphatic fertilizer in relation to nitrogen can cause a nutrient imbalance, thus limiting the effectiveness of the nitrogen applied.

Sustainable use of phosphatic fertilizers

Requirements for calculating nutrient balances already exist in some European countries and at some stage may be introduced in others. Such systems require that the farmer keeps accurate records of the nutrients applied and removed in the harvested crop so that there is evidence that the size of the nutrient balance does not exceed the limit set for each nutrient. For phosphorus, such an approach is acceptable provided that the soil is at, or close to, the critical value. However, where soils are below this level, farmers need to be allowed to apply sufficient phosphorus not only to ensure optimum yields, but also to accumulate the appropriate reserves so that optimum yields are obtained in the future.

Mineral fertilizers are more easily managed than organic nutrient sources yet farmers still require good advice, based on results from reliable field experiments, for the best use of both. The fertilizer industry supports this scientific approach. Studies show that when such advice is available most arable farmers do use mineral fertilizers according to the recommendations. However, in animal husbandry, the value of the nutrients contained in the manure is difficult to assess. In consequence, allowance is not always made for the nutrient input, to the detriment of the environment.

The West European fertilizer industry has long been committed to sustainable agriculture and improved fertilizer use. It has taken an active part in seeking solutions to nutrient related environmental problems, often in co-operation with research institutes, universities, government departments and agencies, and extension services. It has instigated research and development leading to new and improved fertilizer recommendations, frequently based on computer programmes and soil analysis data. This has effectively lead to tailor-made, site specific on-farm nutrient management systems. The fertilizer industry has encouraged the development of the precision farming concept which has led to further improvements in nutrient efficiency, recovery and recycling. On the fertilizer production side, new products and formulas have been developed and the physical properties of fertilizers have been improved. In all these research and development activities, the essential need to minimise environmental risk has been of paramount importance.

The fertilizer industry has accepted the challenge to provide growers with fertilizers of the required chemical composition and physical quality, so that nutrient inputs contribute to sustainable agriculture and any negative impact on the environment, from the use or manufacture of the industry’s products, is minimised.