

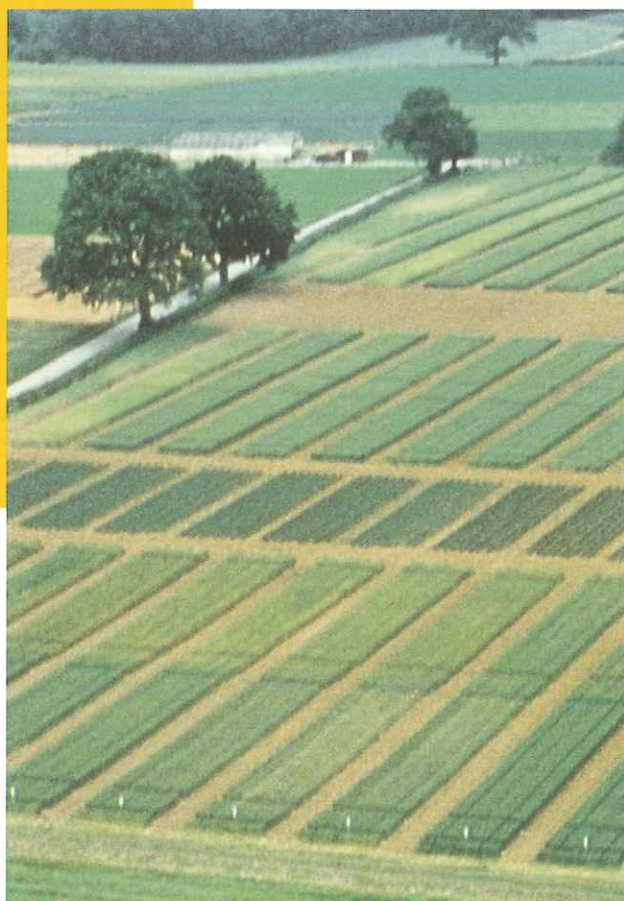
The Efficient Use of Plant Nutrients in Agriculture

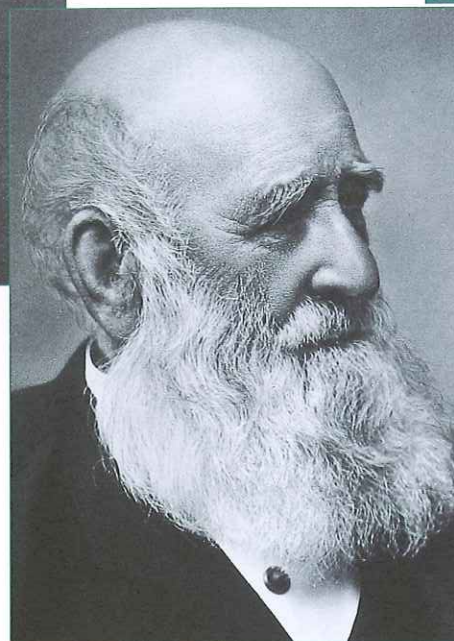
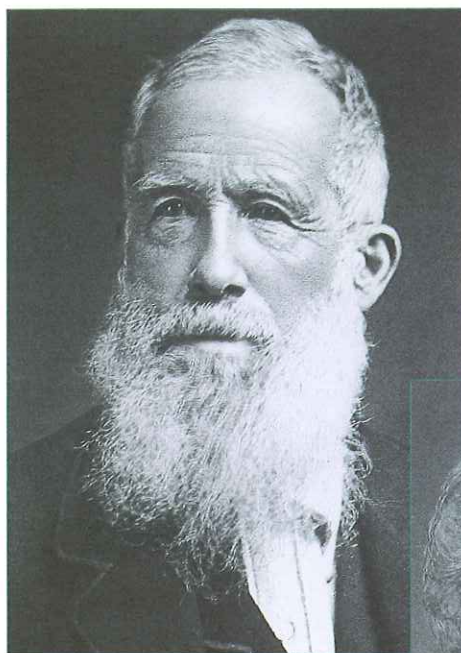


by **A.E. Johnston,**

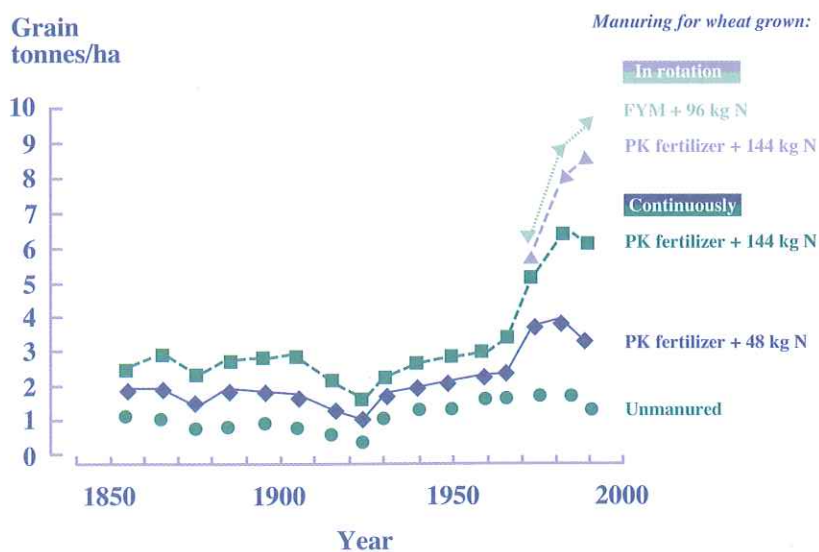
Lawes Agricultural Trust Senior Fellow

IACR Rothamsted





Sir John Lawes (1) and Sir Henry Gilbert (2), who started the Rothamsted experiments in 1843, are regarded as the founding fathers of the scientific method in agriculture.



Winter wheat has been grown on all or part of the Broadbalk experiment every year since 1843. This is a remarkable example of the sustainability of an agricultural system appropriate to the soil and climate. Prior to the 1950s yields were restricted by the limited genetic potential of the crops. The top line labeled FYM (farmyard manure) illustrates the fact that, in order to achieve consistently high yields with modern varieties, a good soil physical condition, through an appropriate amount of soil organic matter, is necessary.

Summary

The existence of humankind depends primarily on an adequate supply of food. Similarly, plants require nutrients which they obtain from the soil. Ancient civilizations expanded as they learnt how to overcome the problems of inherently infertile soils and produce more food; they perished once their agricultural base could no longer support them. Such problems still exist and whilst there is an increased awareness of the effects of population pressure, agriculture is often criticized for its perceived adverse environmental impact, and the increasing need to produce more food is ignored.

The fertility and productivity of soils can vary widely and both depend on many factors. Nutrient management practices for food production must reflect such differences. Fertilizers in whatever form are essential to nourish inherently infertile soils and even with the most efficient nutrient cycling, losses of nutrients from agricultural systems are inevitable and must be replaced. Maintaining and where possible increasing the productivity of agricultural land is essential so that a growing population can continue to be fed in a sustainable way in our fragile world.

Reconciling the twin objectives of protecting our planet while meeting future food needs requires the agricultural and environmental communities to cooperate and to apply the results of continued research.

Introduction

Much is said, written and discussed about sustainable agriculture. The word sustain has a number of meanings of which «to keep going continuously» provides the best definition for the adjective 'sustainable' in relation to agriculture.

The Brundtland Commission defined sustainability as «meeting the needs of the present without compromising the ability of future generations to meet their needs» (World Commission, 1987). This simple statement has immediate appeal as a responsible approach to the use of the world's resources. But use of any finite resource by any generation is ultimately not sustainable. Perhaps the guiding principle should be to optimize use of resources with an emphasis on recycling them where possible. This paper seeks to develop this principle in relation to the use of plant nutrients in agriculture.

Such concepts in relation to agriculture are not new. The following quotation is from Sanskrit, the classical literary language developed from about 1500BC by the Hindus in northern India.

'Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die taking man with it.'

This definition, although so old, has within it the phrase «surround us with beauty» which encapsulates a major concern of today, namely that agricultural practices are damaging the environment, destroying amongst other aspects its beauty. Thus the current dilemma is to sustain, and increase as necessary, agricultural productivity in an environmentally benign way and this also will be discussed here.

Present concerns

There are many reasons why in certain areas many people are hungry for much of the time but elsewhere food production is in surplus. Surpluses are bad for farmers if they keep prices low but in some countries they are often favoured politically because they provide cheap food. However, surpluses have encouraged some people in the industrialized nations, who have become increasingly concerned for the environment, to attack agriculture because they see its profligacy as contributing to environmental degradation. Such individuals and groups have attracted widespread attention to those aspects of current agricultural practices which they consider to be dangerous or objectionable. These include animal husbandry systems perceived by some to be unnatural or degrading, landscape changes, loss of wildlife habitats, soil erosion and loss of soil fertility, pesticide residues in soil water and foodstuffs, nitrate in many ground and surface waters and eutrophication of surface water with nitrate and phosphate leading to the occurrence of algal blooms. Threats to the environment, and ultimately humankind, are the cumulative effects of many industrial and social practices, not only agriculture. For example, large scale pollution, as with acid rain; major accidents, as at Chernobyl; destruction of important habitats, as in the Amazonian rain forests; the wasteful exploitation of the world's mineral and biological resources because of a lack of desire or opportunity to recycle; and global problems, such as the greenhouse effect, are frequently acknowledged to exist but are thought to be too immense for individual action. Criticism of agriculture tends to be confined to developed countries where a wide range of foodstuffs is available from all over the world. It is rarely appreciated that food imported from poor, developing countries may have been produced at some cost to them and their environment.

It is equally important to acknowledge that improved husbandry systems have enabled many more people to be fed than could have been supported previously. High outputs are the result of many

interacting factors; farming skills in the use of new cultivars with a higher yield potential, optimal inputs of nutrients, the judicious use of agrochemicals to control weeds, pests and diseases and where necessary the efficient use of water. Inevitably, such farming has some environmental impact. Eutrophication - the enrichment of surface waters with nutrients - probably first began 10,000 years ago when Neolithic man cleared natural vegetation, such as forest and grassland, to grow crops. The present concern is whether current farming practices cause unacceptable harm and environmental change. This involves judgments of morality, benefits and costs. Unfortunately, decisions are often based only on political considerations rather than available scientific facts and understanding. The need to feed people or improve their standard of living by cultivating land may prevail over maintaining a diverse flora and fauna.

In retrospect it can be seen that some decisions, such as bringing marginal lands into agriculture, have had catastrophic consequences for the environment. Conversely, unscientific and unjustified measures may be applied to agriculture in response to environmental concerns leading to unnecessary burdens being carried by agriculture such as attempts to limit nutrient losses to unattainably low levels.

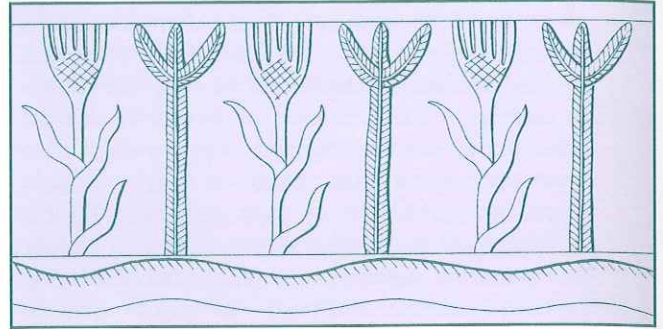
Historical perspectives

For perhaps two million years humankind sustained itself by gathering and hunting food, moving when necessary to find fresh sources. Throughout this long period the population, whilst small in number, adapted to its environment with minimum impact.

Then, perhaps 10,000 years ago, starting in the Neolithic era, more organized agricultural systems were developed based on soil cultivation to grow food crops. This change accompanied the first settled societies in at least three separate locations, south west Asia, Mesoamerica and China. Within these societies, primitive agriculture allowed farmers to produce sufficient food for non-producing urban populations. These increasing populations put ever greater demands on the fragile resources available for food production and short-term demands began to out-weigh any considerations for long-term stability and the development and maintenance of sustainable agricultural systems.

In Mesopotamia, the Sumerian society which, starting about 3000BC, became the first literate society in the world, then gradually perished as its agricultural base declined. Always dependent on extensive and complex irrigation systems, the need to provide food for the expanding population forced agriculture on to unsuitable and vulnerable soils. The combination of weather patterns, soil type and deteriorating water quality, led to increasing salinization. In consequence crop yields per

hectare declined by 65% between 2400 and 1700BC.



Wheat and? flax on a Sumerian vase

In Mesoamerica the earliest settlements of the Mayan society date from about 2500BC. Intellectually this society was remarkable, particularly in its study of astronomy, yet once decline set in, it collapsed within a few decades. The Mayans appear to have had an intensive agriculture growing food in terraced fields on the hillsides and raised fields in swampy areas. As their civilization developed, the elite amongst the city dwellers began to demand greater numbers of elaborate ceremonial buildings which required timber taken from the remaining hillside forests. In addition, fuel was removed from the forests and the labour for this and the construction projects was withdrawn from food production. Concurrently an ever-larger army was required to protect each city from its neighbours. Population pressure here, as in Mesopotamia, pushed agriculture onto marginal land and by 800BC there is evidence of a serious decline in production. Soil, eroded from the steep hillsides following forest clearance, was deposited in the terraced fields and blocked drainage ditches. Labour taken for the army and city projects was not available to make good the damage. Declining availability of food and an increase in fighting for scarce resources quickly led to the disappearance of this once sophisticated civilization. Mayan cities and fields were rapidly reinvaded by the dense jungle surrounding them and remained lost until discovered in the late 1830s.

These are but two examples of the rise and fall of great civilizations which perished when their agriculture could no longer support them. They were chosen because salinization and deforestation leading to soil erosion, are two of the major threats to the sustainability of agriculture today.

Past agricultural practices in Asia, Europe and America

China, one of the three regions in which settled societies first developed, is now the world's oldest civilization. In China, as in much of Asia, the diet was based largely on pigmeat and irrigated rice. For thousands of years farmers practiced excellent management of the cultivated land. As late as 1949, organic sources provided more than 98% of the nutrients applied to soil, now the proportion is less than 38%. However, throughout its long

history there have been inevitable losses of nutrients from the soil-plant-animal cycle. Historically, these losses were compensated for by the transport of plant materials and the erosion of vast quantities of soil from the uplands to the intensively managed, carefully husbanded lowland fields. Over centuries this practice of allowing the transfer of soil and plant residues, with their precious organic matter and plant nutrients, produced fertile lowlands but the deforested and denuded uplands became incapable of supporting viable agricultural production. Whilst this transfer maintained the productivity of the lowlands, and undoubtedly helped feed China's increasing population, it is essentially a «one-off» process and therefore not sustainable in the long-term.

Development of agriculture in Europe was similar to that in Asia. Initially based on shifting cultivation, population pressure caused more and more afforested land to be cleared and used for food production. Although perhaps 95% of West and Central Europe was originally covered by woodland, this proportion has fallen to 20%. Early land clearance did not lead to serious soil erosion as it did in China - no extensive terracing is found in West Europe. But with no other means of replenishing nutrients, newly cleared land was incapable of giving acceptable yields of food crops year after year. Techniques of cereal-fallow and later cereal-legume-fallow rotations were practiced as early as Roman times. These were gradually replaced with mixed farming with animals and crops.

By the mid 18th Century in England, the Norfolk Four-Course Rotation was being practiced - cereals and root crops were grown in rotation with grain legumes and grass-clover mixtures providing food for humans, cattle and the work horses. Because a large proportion of the crops produced on the farm went to feed animals, especially horses, and only cereal grain, milk and meat were sold off the farm, much of the nutrient content of the harvested crops was returned to the land in farmyard manure (FYM also called animal, stable or barnyard manure). The requirement for the tenant to do this was often included in agreements between landlords and working tenant farmers.

As the urban population expanded rapidly in the Industrial Revolution of the late 18th and early 19th centuries, farmers strove to increase production. Initially, observation rather than research identified the need for phosphorus (P) for root crops and phosphorus and potassium (K) for legumes.

The production of superphosphate, from the early 1840s, and the mining of potash salts and production of potash fertilizers from the 1860s, provided sources of both nutrients in plant available forms. Nitrogen (N) became available to farmers as ammonium sulphate or sodium nitrate to supplement that supplied in organic manures or by biological fixation. The use of P and K fertilizers resulted in a very gradual build up of these nutrients in soils over most of West Europe during a 60- to 100-year period, whilst the use of lime (CaCO_3) maintained soil pH.

A third scenario is seen in North America. Poor emigrant farmers from Europe who settled in North America in the latter half of the last century found soils whose organic matter content had been increased under natural vegetation during hundreds of years. An exploitive arable agriculture, with little return of plant nutrients and in a climate few of the settlers from North Europe had experienced, rapidly depleted this organic matter. Declining yields and the dust bowls of the 1930s were the result. Unlike more ancient civilizations, a young and vigorous nation with a will to survive, and an improving technology and understanding of soil processes to support that will, put in place measures to rebuild nutrient levels and minimize the damaging effects of declining levels of soil organic matter.

The 1960s to 1990s

Food shortages in the Second World War led many post-war governments to make the security of their food supplies a first priority. At the same time other countries saw a major market opportunity in supplying food to those whose productive capacity had been devastated by war. The increase in the productivity of land in the agriculturally developed countries since the 1950s has been remarkable, especially when viewed against the background of almost unchanging yields in the previous 100 years.

The all-round desire to increase food production at any cost was aided by a number of factors. One was the increasing reliability of mechanical tractive power to replace horses which freed land for producing human food. Another was the increasing availability from the late 1950s of cheap nitrogen (N) fertilizers. The increasing use of nitrogen throughout the world was justified by a number of other factors. Plant breeders produced cultivars of staple food crops with an increasing yield potential. More effective agrochemicals to control weeds, pests and diseases were developed so that the yield potential of the new cultivars could be achieved under field conditions. Irrigation was used more extensively.

In Europe and North America there was also an increase in the use of P and K fertilizers. In Europe this allowed high yields to be achieved while maintaining the soil fertility which had been built up slowly by manures, fertilizers and crop residues during the previous decades. In Asia, the benefits of using N fertilizers were quickly apparent. But, in contrast to Europe, N was increasingly used on soils where there had been little accumulation of P and K during the previous decades. In consequence there is now concern about nutrient imbalances and the increasing risk of soil nutrient depletion which could threaten the food security of the region.

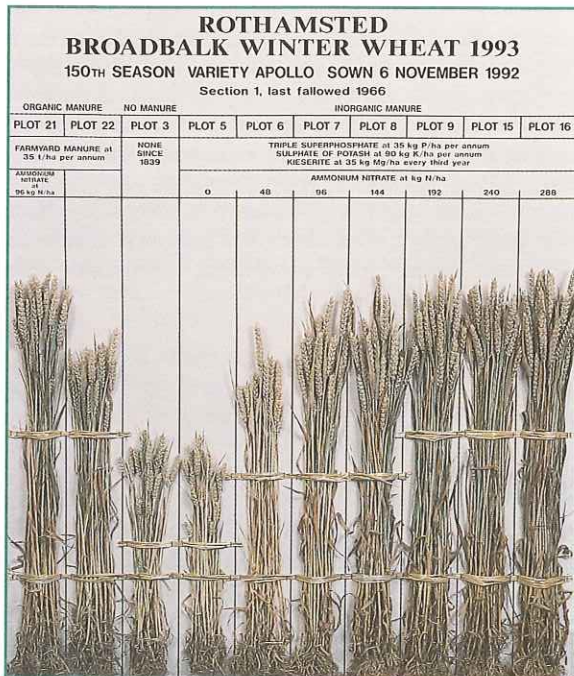
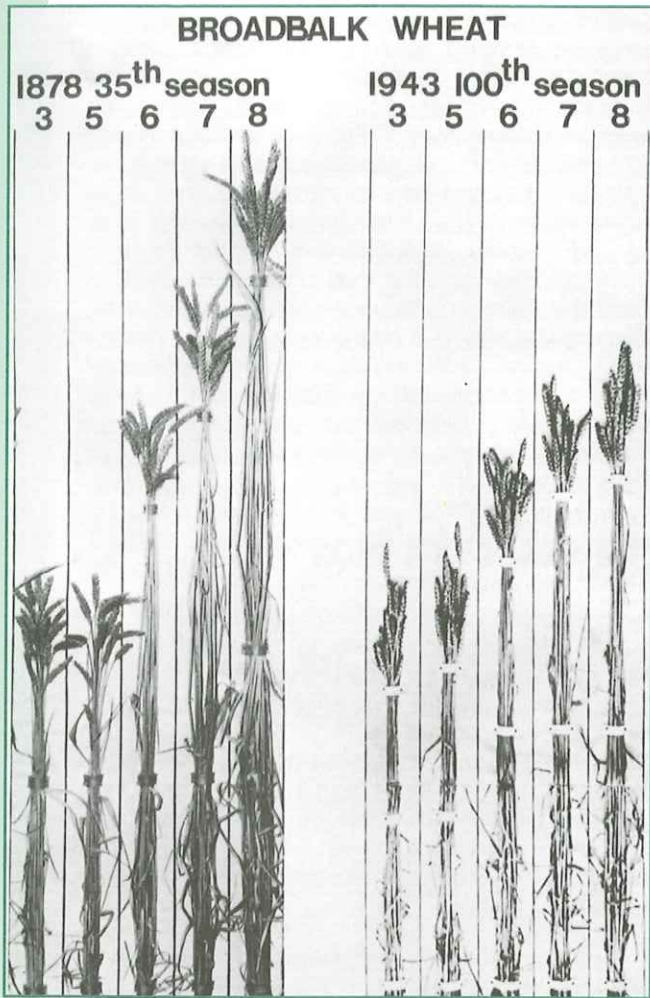
SOIL FERTILITY AND CROP PRODUCTIVITY

Any discussion of sustainability related to the managed use of land must include physical, environmental and socio-economic aspects. No agricultural system will be sustainable if it is not economically viable both for the farmer and society at large. But economic sustainability cannot be bought at the cost of either environmental damage, which is ecologically, socially or legally unacceptable, or of physical damage, which leads to irreversible soil degradation or uncontrollable outbreaks of pests, diseases and weeds.

Currently, yield is often the only true measure of sustainability because the plant itself integrates across all factors, including soil, climate, pest and disease, which affect growth. But monitoring sustainability in this way requires yield data over many years so that «trends» can be separated from «noise», caused by temporary variations due to weather or management. It would be preferable, therefore, to have soil indicators and thresholds associated with them, the breaching of which would provide early warning that yields may face decline. Because many of the properties which affect soil fertility change slowly over many decades, especially in temperate climates, it would be useful to have simple procedures that allowed routine analyses on many soils over long periods.

Although it might seem desirable to work towards a single, worldwide index for the sustainability of land use, this is likely to be difficult to achieve in practice and might not even be very helpful. This is because any agricultural system is only as strong as its weakest link which may be any one of a wide range of variables such as soil type, soil fertility, climate, water availability, management skill or financial viability; these and other variables will not always rank in the same order. Thus a critical level set for any parameter controlling yield may well differ between soils, farming systems and climate. It would be sensible, therefore, in any search for critical values of soil parameters to attempt to determine them for a wide range of systems. The aim would be to provide general guidelines from which site-specific management plans can then be devised and implemented.

Soil fertility is not synonymous with agricultural productivity. Indeed, since the 1950s it is attempts to increase productivity, without sufficient regard to soil fertility, that have led to many of the concerns about the impact of agriculture on the environment in some countries. For example, the movement of nitrate and pesticide residues to potable water is blamed on the increased use of nitrogen fertilizers and pesticides, respectively. In consequence, it is necessary to make a clear distinction between soil fertility and productivity. What is certain is that attempts to increase productivity, by for example simply applying more N fertilizers, are doomed to failure without adequate soil fertility.



Agricultural productivity in the temperate regions today owes much to plant breeding. This is especially so for cereals; the large change in the ratio of grain to straw has permitted a great improvement in yield. These photographs show winter wheat grown on Broadbalk field in 1878, 1943 and 1993. They show clearly the shortening of the straw during this period. The numbers 3 to 8 relate to the plots to which the different fertilizer treatments were applied. Plot 3 received no fertilizer. Plot 5 received phosphate and potash. Plots 6 to 8 received phosphate, potash and respectively three levels of nitrogen.



Nitrogen and biocides should be thought of as controlling agricultural productivity rather than contributing to soil fertility. Nitrogen can be supplied by fertilizers, organic manures or biological fixation

Soil fertility

The fertility of soil can be defined as its capacity to supply adequate nutrients to produce a desired plant community or crop. Each will vary in its nutrient requirement. Nutrient requirements increase in the progression from natural forest to extensively grazed grasslands to arable crops to intensively managed vegetable crops. Soil fertility develops slowly over many decades, but inept management can destroy it rapidly, yet small, less obvious, insidious changes can be equally damaging in the long term.

Soil fertility arises from complex interactions between the biological, chemical and physical properties of soil. The difficulties of defining and quantifying the parameters controlling soil fertility are exacerbated by the fact that many of the factors are rarely in equilibrium. Moreover, little is known about the complexity of some of these interactions or their rates of change, especially in relation to our ability to predict variations in soil fertility.

Biological properties

Biological properties include both beneficial and harmful organisms. Beneficial organisms include mycorrhizal fungi, which for certain crops can play a role in enhancing phosphorus uptake by roots growing in phosphorus deficient soils. Some free-living, non-symbiotic organisms, like blue green algae, can fix atmospheric nitrogen and reduce the need for N fertilizers. Many bacteria and fungi break down organic residues from both plants and animals and this process recycles plant nutrients and produces humus. Conversely, soil-borne pathogenic organisms can seriously decrease yields. Whilst some can be controlled, the use of appropriate chemicals can leave residues the effects of which have yet to be quantified, and for others there is no effective chemical control currently available.

Physical properties

Physical properties encompass soil density, water holding capacity and rooting depth. Plants growing in shallow soils overlying impervious strata will always have a limited volume of soil to exploit for nutrients and water and such soils will invariably

have a low yield potential. Similarly, the yield potential of light textured, sandy soils will be less than that of heavier textured soils unless irrigation is available. If yield potential is small then the amount of added nutrient required may also be small. The management of available water will be critical in many areas and it is essential to maximize the efficiency with which it is used to produce harvestable produce. In areas of low rainfall techniques to improve water infiltration will also help to minimize erosion risks. Encouraging plants to root at depth enables them to use subsoil water. Where irrigation is practiced the quality of the water is important and its use must be managed to minimize salinization.

Chemical properties

The most important chemical properties are soil pH, P and K status and organic matter content but the availability of secondary nutrients and trace elements can also affect yield. Where liming materials are available it is usual to recommend that soil pH in water is maintained at pH 6.5 for arable crops and pH 6.0 for grassland because the availability of most plant nutrients is near optimum in this pH range. Increasing soil acidity increases the amount of aluminium, iron and manganese in the soil solution and it is these elements, in ionic forms and especially Al_3^+ , rather than acidity per se which adversely affects growth. To some extent the effects of Al_3^+ are less severe in the presence of phosphate. But raising levels of P to ameliorate Al_3^+ effects can be costly although the placement, or banding, of P applications with seeds can help. Where liming materials are not readily available one way forward will be to breed plants tolerant of acidity.

Soil organic matter

Freshly added organic matter, as plant and root residues and organic manures, are a food source for the soil microbial population and its activity produces soil organic matter or humus. This can give small, but perhaps important increases in water holding capacity as well as providing plant nutrients during its breakdown; the latter is especially important in natural ecosystems. Humus also has an important role in retaining P, K and magnesium (Mg) in plant available forms.

In temperate soils the amount of humus usually changes slowly over time and any benefits from it have been difficult to measure unequivocally in the past. For example, for more than 100 years annual additions of fertilizers and farmyard manure have given very similar yields of arable crops in experiments at Rothamsted, England, on a silty clay loam soil. This was still so even in recent years although FYM-treated soils contained about 2.5 times as much humus as soils given only fertilizers. The significance of this was that both fertilizers and FYM supplied the requisite plant nutrients in forms available for uptake by plant roots. Recently, however, yields on FYM-treated soils given extra fertilizer nitrogen have been lar-

ger than those on soils treated only with fertilizer irrespective of the amount of nitrogen applied on the latter. On the fertilizer-only soils, humus levels have not declined in recent years. The larger yields are therefore probably the result of better soil physical conditions on FYM-treated soils enabling modern, high-yielding cultivars to achieve their potential yield. In this new situation the benefits of soil organic matter should not be underestimated.



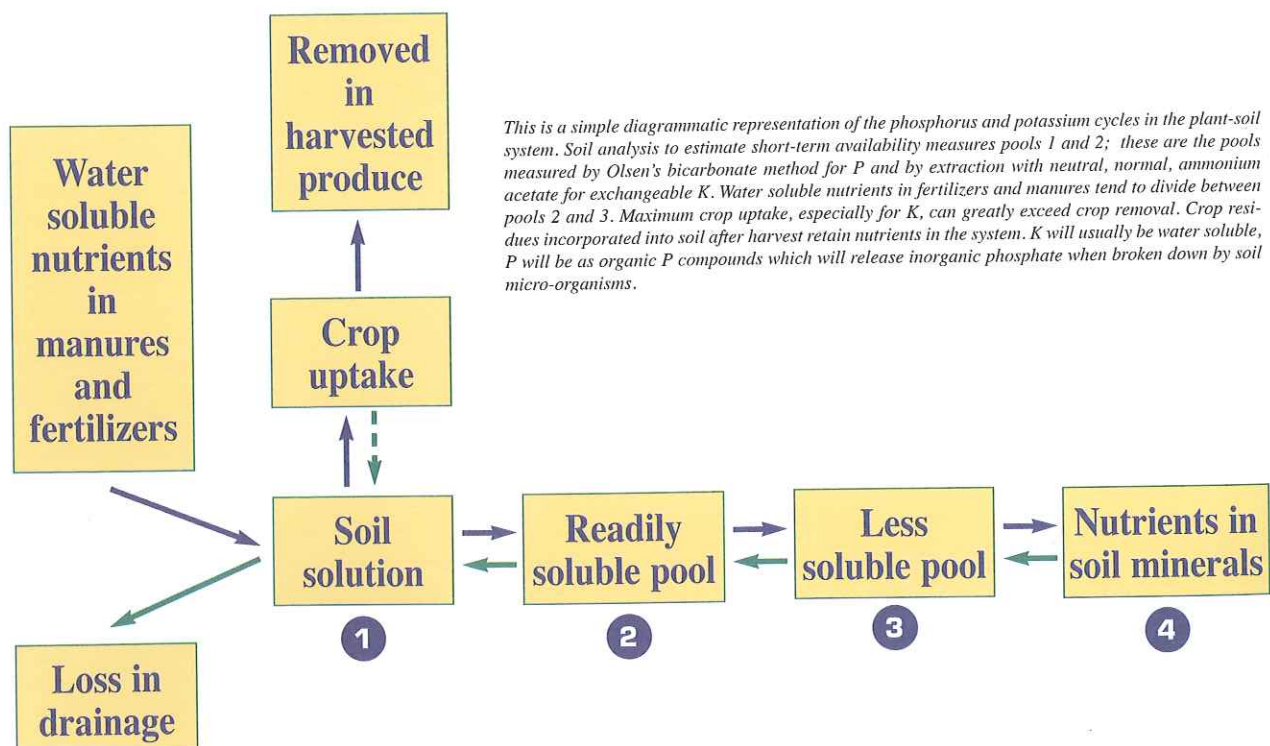
To achieve consistently high yields with modern varieties requires a good soil physical condition, through an appropriate amount of soil organic matter.

Soil phosphorus and potassium

J.B. Lawes of Rothamsted took out a patent for the manufacture of superphosphate in 1842 and by mid 1843 had a factory at Deptford, London, in commercial production. This was not done in the hope of making money but because Lawes knew that one of the principal sources of phosphate -

bone products - then available to farmers, was not effective on the slightly calcareous silty clay loam on his farm. Together with a chemist, J.H. Gilbert, he proved in field experiments that the water soluble phosphate in superphosphate increased the yield of arable crops whereas insoluble phosphates would not. Research on P and K has continued ever since both at Rothamsted and elsewhere worldwide and the understanding of soil processes involving these two nutrients in relation to crop nutrition has developed considerably, especially in the last 30 or so years.

At the turn of the century experiments showed there was little residual value from one application of P and K applied in water soluble fertilizers. A water soluble P fertilizer was therefore assumed to have no further value after three crops had been grown, whilst a K fertilizer had no value after two crops. It was assumed that the residue had by that time become fixed in the soil and was unavailable to further crops. International soil research conceptualized these ideas during the next 20 to 30 years and expressed them diagrammatically as shown below. Phosphorus and potassium were considered to be in different «pools» or «categories». Adding water soluble fertilizers to soil, supplied nutrients to the soil solution from which they were taken up by plant roots. But their water solubility declined quickly so they became part of the readily soluble pool and then passed into the fixed pool. At that time research and advice to farmers emphasized this transfer from left to right through these pools.



This is a simple diagrammatic representation of the phosphorus and potassium cycles in the plant-soil system. Soil analysis to estimate short-term availability measures pools 1 and 2; these are the pools measured by Olsen's bicarbonate method for P and by extraction with neutral, normal, ammonium acetate for exchangeable K. Water soluble nutrients in fertilizers and manures tend to divide between pools 2 and 3. Maximum crop uptake, especially for K, can greatly exceed crop removal. Crop residues incorporated into soil after harvest retain nutrients in the system. K will usually be water soluble, P will be as organic P compounds which will release inorganic phosphate when broken down by soil micro-organisms.

Since the 1930s many different extractants have been tested as estimators of the concentration of P and K in the readily soluble pool and experiments were made to relate the data to the response of crops to fresh applications of fertilizer in the field. It was appreciated, however, that in unamended soils, like natural grasslands and forests, the availability of P and K depended on the release of these nutrients from reserves within the mineral matrix. The amounts released were often very small - 3 to 4 kg P, 20 to 25 kg K per hectare each year on the silty loam at Rothamsted - clearly such quantities were too little to grow acceptable yields of food crops.

In the late 1950s a major research programme involving field and glasshouse experiments and associated laboratory studies was started at Rothamsted. Olsen's bicarbonate method for P, bicarbonate-P, and exchange with ammonium acetate for exchangeable K, were considered to be the most appropriate methods to determine the readily soluble pools of P and K on these soils. Both these methods are now used in many laboratories worldwide, but they are not universal. Data given by these two methods gave a good index of the availability of P and K to crops and very adequately indicated the likely response to a fresh application of either fertilizer.

Arable crops and grass gave larger yields when grown on soils enriched with residues from past applications of both fertilizer and organic manures. As important, it was found that adding large amounts of fresh fertilizer to impoverished soils rarely increased crop yields to match those on enriched soils. This result was subsequently confirmed by other research groups. In summary, the accumulated residues from repeated applications of P and K in fertilizers and manures enriches the soil to the benefit of crops, there are analytical methods capable of indicating the size of these residues and, most importantly, it was shown that both P and K could transfer from the readily soluble to the soil solution pool.

Subsequent research showed that residues in the non-readily soluble pool also became available to crops once the soil solution and readily soluble pools were stressed, or drawn upon, to meet crop demand. The reversibility of the pathways in the diagram was established; P and K residues were not irreversibly fixed in these soils. This has been shown to be true also for many other soils but not for all. There are soils, many in the tropics, which are highly weathered and contain a variety of constituents, like sesquioxides and some minerals which fix and retain large quantities of either or both P and K in forms which are not available to plants. On such soils much more thought must be given to methods of applying P and K so that they continue to be available for crop uptake for as long as possible.

The demonstration that P and K residues in soil were of great benefit to crop growth led to the question, «To what extent should residues be increased?» Subsequent experiments examined the relationship between yield and bicarbonate-P

and exchangeable K. For the arable and grass crops grown, yields increased rapidly at the lower levels of readily soluble P and K and then more slowly to approach a plateau. This type of response has been confirmed in many other experiments. Thus, in summary, below a critical level of readily soluble P and K in soil at which yields reach a plateau there is a serious risk of loss of yield and farmers should be encouraged to increase soil levels until the critical value is just exceeded. To go much beyond the critical value can be an unnecessary expense to the farmer. Occasionally, levels are so much above the critical values that adding no P or K could be the best option for a limited period. This often happens when animal manures from intensive livestock enterprises are applied to land in large quantities. The adverse effects of P lost to rivers and lakes from agricultural soils are discussed later. There is no indication that losses of K have any adverse environmental impact.



An experiment testing phosphorus levels in soils showed acute phosphate deficiency in sugar beet. It also showed that there was a critical level of readily soluble P in soil, measured by Olsen's bicarbonate method, below which the loss of yield was financially catastrophic for the farmer. Above this critical level, which was independent of yield, there was no economic justification for increasing soil P levels further. There is also an increased risk of loss of P from soils highly enriched with P. Such losses are a contributory factor in the growth of algal blooms in lakes.

Although critical values for readily soluble P and K vary according to the crop the range is not excessive and this suggests that it would be sensible to maintain soils near to the value for the most sensitive crop grown in a farm rotation. Also when soils are above the critical level fertilizers and manures need only be applied periodically; the amount of P and K applied at one time should be sufficient to meet the needs of three or four crops.

Secondary nutrients and trace elements

As the problems of major nutrient deficiencies are corrected the need for secondary elements, like calcium and magnesium, and trace elements like zinc and boron become apparent. Such deficiencies are not always obvious but can seriously limit yields. Very often they need to be identified by a combination of soil and plant analysis.

Crop productivity

Climatic factors are outside the control of the farmer although water deficits from too little rainfall can be corrected where irrigation is available. Also, drainage systems can aid the removal of surplus water. However, within the constraints of climate, provided soil fertility is optimum, crop productivity can be controlled by varying inputs like nitrogen and pesticides. Nitrogen can be applied as fertilizers and in organic manures or, where appropriate, atmospheric nitrogen can be fixed microbially.

Nitrogen

Even in the late 1830s there was still much uncertainty about the source from which plants derive their nitrogen. It was Lawes and Gilbert's famous large scale field experiments, started at Rothamsted in 1843, that provided the first convincing evidence that plants, other than legumes, required a readily assimilable source of combined nitrogen in the soil solution for uptake by roots. This combined nitrogen could be either nitrate or ammonium and the experimental results showed that the supplies in soil were too small to give satisfactory yields of crops and had to be supplemented by organic manures or nitrogenous fertilizers.

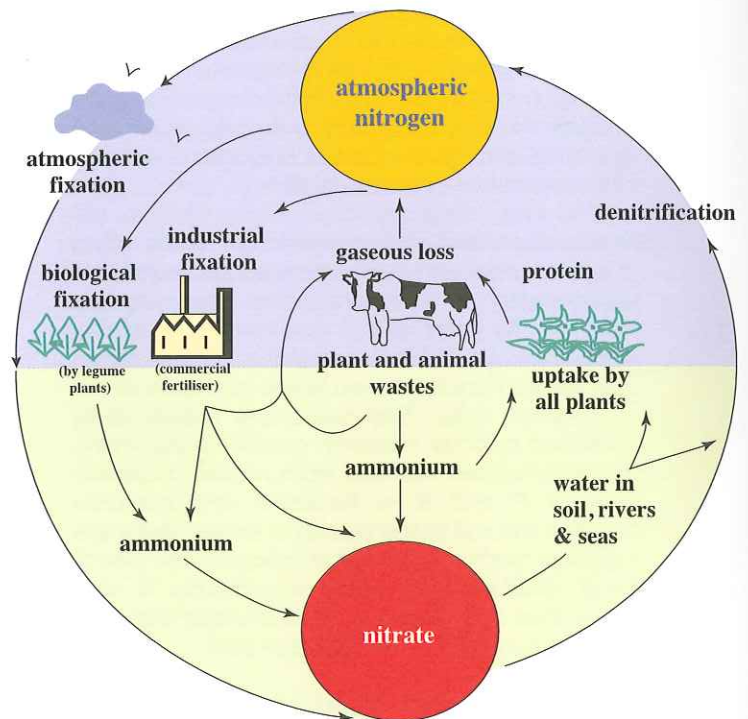
Farmers began to appreciate the significance of the Rothamsted results and, over the next 50 years, there was a gradual increase in the use of N fertilizers. By the 1890s there was concern that the known supplies of combined nitrogen readily available for agriculture, ammonium sulphate from town gas manufacture and sodium nitrate from Chile, would not meet the increasing demand. Commercially viable ways were therefore found to «fix» some of the vast quantities of nitrogen in the atmosphere.

The agricultural use of nitrogen stagnated in the agricultural depression of the 1920s and 1930s and was restricted by the need for explosives in the 1939-1945 war. With the end of that war came the capacity to produce N fertilizers for agriculture. Their increased use since then is well documented.

Nitrogen is taken up by plants as ammonium or nitrate ions. The principle store of nitrogen in soil is as organic nitrogen compounds in humus and some of the nitrogen in organic manures is also added in similar compounds. Microbial activity decomposes these organic N compounds to produce first ammonium ions and then nitrate ions. Most soils can retain ammonium ions but usually the amounts are small because they are rapidly converted to nitrate. Unfortunately only a very few soils have a mechanism which will retain nitrate similar to that which retains ammonium, phosphate or potassium ions. Also nitrate is very soluble in water and whenever excess rainfall leads to drainage, nitrate will be at risk to loss by leaching either to surface waters or to underground aquifers. Besides being lost in solution, nitrate can also

be lost from soil both as nitrogen gas and as nitrous oxide when another group of microbes break down nitrate in oxygen deficient soils. Nitrogen is harmless but nitrous oxide is a greenhouse gas.

The microbial decomposition of organic matter rarely provides sufficient N to meet the maximum needs of agricultural crops. There is also another problem. Soil conditions for decomposition are often optimum when crop demand for N is either non-existent or very small so that most of the nitrate produced then remains mobile in the soil and at risk to loss by leaching. For these reasons N fertilizers applied to actively growing crops usually give large increases in yield. However, the amount applied should be adjusted to supplement and not substitute for the supply of nitrate from organic matter otherwise much nitrate from whatever source will be at risk to loss by leaching.



The agricultural nitrogen cycle, i.e. the different pools of nitrogen in the soil-plant-animal system and the pathways by which N is transferred between the pools, is complex. It is difficult to control the system to maximize the benefit to agriculture while minimizing the adverse environmental impacts of the loss of nitrate. In part this is because microbial activity, which is very difficult to control, plays a major role in the cycling of nitrogen.

Pesticides

Pesticides are not a topic of this paper but are mentioned briefly because, as discussed earlier, their use to control weeds, pests and diseases often allows crops to utilize nutrients efficiently. Today, integrated pest management, which seeks to capitalize on the use of natural predators and

other natural control mechanisms, is a major area of research effort.



Systemic fungicides became generally available in the late 1960s. Before then, diseases such as eyespot, if too much nitrogen fertilizer was applied, caused cereals to lodge, with severe loss of yield.

Fertilizers, the environment and research

Farming is a complex, biological activity which by its very nature interacts extensively and sometimes intensively with the wider environment in which it functions. Research at many levels is therefore required to provide the basis on which sound judgments can be reached in response to legitimate environmental and agricultural concerns.

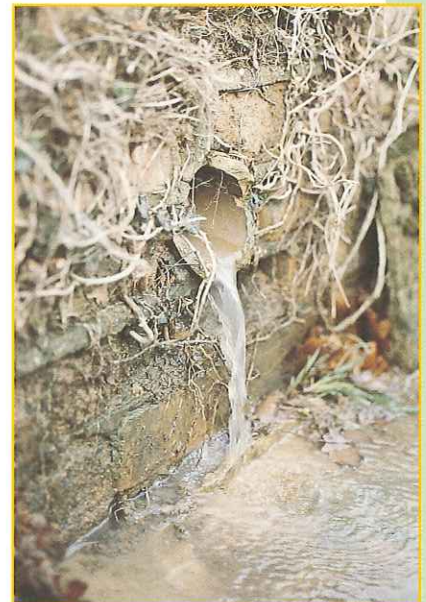
In the last century observation suggested that crops benefited from applying bones to some soils, but it was research which identified that water soluble phosphates were effective on all soils. Although it was observed that FYM increased crop yields, it was research which identified that much of the benefit stemmed from its readily available nitrogen content. There are many other examples and perhaps today research has a greater role to play than ever before as the following examples serve to illustrate.

Nitrate leaching from agricultural land

Increasing levels of nitrate reported in many potable waters in the 1960s and 1970s in West Europe and North America were linked to the increasing use of nitrogen fertilizers on agricultural land. It took some fairly long-term and expensive research with N_{15} -labeled N fertilizers to show that if they were applied at the correct time and in the right amount to an actively growing crop so that it could achieve its yield potential, then very little fertilizer nitrate remained in the soil at harvest at risk to loss by leaching. This was especially so for cereals and grass cut for conservation. Most of the nitrate which appeared in soil after harvest, and was at risk to loss by leaching when there was through drainage, came from the mineralisation of soil organic matter. However, for some crops like vegetables, which appear to require much N, a great deal of nitrate can remain in soil.

The continued use of N fertilizers to produce larger yields of arable crops will give small increases in humus because larger crop residues are incorporated into soil each autumn. To this extent the use of N fertilizers may be said to increase the nitrate levels in soil in autumn. However, the amounts are likely to be small compared to those coming from the decomposition of recently ploughed grassland or the incorporation of nitrogen-rich plant or organic residues. Research seeks ways of diminishing nitrate levels in autumn by, for example, comparing the effectiveness of various cover crops.

Research has also shown that well managed grazed grass-clover swards can lose as much nitrate in autumn/winter as all-grass pastures given 300 kg N/ha. At a more fundamental level, a better understanding of the mineralisation process might allow the development of strategies to control such losses in environmentally-friendly ways.



Grass/clover leys can be used in financially viable mixed farming systems, but, when ploughed in autumn, their decomposition produces nitrate with a risk of loss by leaching during winter. Equally, excessive use of nitrogen fertilizers can also lead to the risk of loss of nitrate in autumn.

Phosphorus leaching from agricultural land

This is a more recent problem than that of nitrate leaching. The consensus view is that nitrate and phosphate concentrations in surface water control algal growth which in large amounts becomes an algal bloom. On the death of these algal blooms the water becomes deficient in oxygen and toxic chemicals can be released in their decomposition. Both or either of these conditions can have catastrophic effects both on living organisms in the water, like fish, or on animals drinking the water.

The effluent from sewage treatment works has been implicated in the increase in phosphate concentrations in surface water but such a point source is relatively easy to control. The critical level for phosphorus for algal growth is very low, perhaps less than 90µg P/litre (90 parts per billion) and such a concentration could be exceeded

in some rivers by loss of phosphorus from agricultural land in the surrounding catchment.

Before agriculture and the fertilizer industry are uniformly condemned for eutrophication, research needs to identify the pathways of loss, the conditions favouring loss and the quantities of N and P lost. Surface run off, especially of recently applied slurry and perhaps of P fertilizers, needs to be quantified. Soil erosion to water courses is an easily identified and well-known loss. Management practices that prevent erosion should therefore have the highest priority. It is also believed that soils enriched with phosphorus well above the critical values needed for crop growth, which are discussed above, could be a major source of contamination. Leaching of phosphorus to tile drains and hence to surface water could be as inorganic or organic phosphate ions in solution or as adsorbed phosphate on particulate matter, either mineral or organic particles, transported down through the profile. However, P leaching is more likely to come from soluble organic fractions rather than mineral fertilizer. Research is needed to establish effective preventative measures.

Pollution from cadmium

There is concern about human exposure to cadmium (Cd) because of possible long-term effects on health. It is generally accepted that plant based foodstuffs are the most important source of dietary cadmium. Plants take up cadmium from the soil and P fertilizers can be a major source of soil cadmium, depending on the content of the rock source. In most industrialized countries, atmospheric deposition of cadmium is also important because of aerial emissions from various processes. For example, cadmium budgets for the UK in the early 1980s estimated that about 15 t cadmium were released to the atmosphere each year of which nearly 90% came from four sources: municipal waste incineration, non-ferrous metal production, iron and steel production and fossil fuel combustion. Although airborne cadmium has been declining since the mid- 1960s there is still a cadmium burden in soil from this source.

as in those receiving no superphosphate: i.e. the cadmium in superphosphate cannot be accounted for. There has been some accumulation of cadmium from superphosphate in acid soils with a larger organic matter content. Further research is needed to understand the importance of organic matter and pH in relation to cadmium retention in soil and its plant availability.

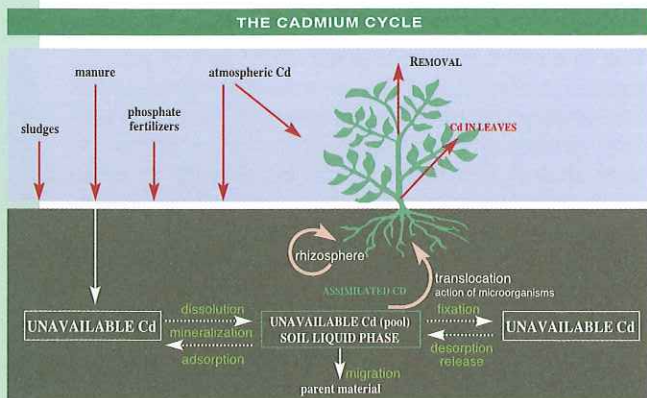
Research elsewhere indicates that cadmium deposited on leaf surfaces can get into plants. It is also known that some plants such as leafy vegetables contain more cadmium than cereal grains. Research is continuing into phosphate fertilizer production processes to reduce the cadmium content of the product, but an effective method is still some years away. At the same time, aerial emissions from non-agricultural processes must be controlled.

Nutrient recycling

By the late 1840s, Lawes and Gilbert's experiments at Rothamsted had shown unequivocally that NPK fertilizers could give the same yields as 35 t/ha FYM supplying 225 kg total N, 40 kg total P and 160 kg K provided the FYM was applied each year. FYM was a valuable source of plant nutrients but large amounts had to be applied because all the N and P were not as readily available in the year of application as were the nutrients in water soluble fertilizers. However, Lawes and Gilbert saw that there was an essential need for fertilizers, not as a replacement for FYM, but because they realized that farming systems based on mixed crop and animal husbandry would never have enough FYM to produce the yields needed to feed the rapidly expanding population following the Industrial Revolution in Britain.

As farming became more intensified and specialized, especially since the 1950s, with animal and crop husbandry often not practiced on the same farm, animal wastes became a disposal problem rather than a source of nutrients. Now many of the environmental problems with nitrate and phosphate arise from the application of excessive amounts of such wastes to minimum areas of land.

This tendency for FYM to be disposed of rather than properly used arises because efficient use requires additional management skills and the equivalent nutrient value can be cheaply purchased as fertilizer. Disposal of FYM rather than its efficient use can result in nitrate and phosphate pollution of water from excessive applications and wastes phosphorus, a finite resource. Therefore, the need to recycle plant nutrients efficiently must be actively promoted. This includes nutrients from animal and food processing sources and also sewage sludge providing it contains little inorganic and organic pollutants. The public perception of agriculture will be much improved if it is seen to take a responsible attitude to such problems. Further investment in research and development will be required to develop an all-embracing concept of plant-nutrient management.



source adapted from Metzger et al.- INRA, 1989

Interestingly, research in the UK showed that the increase in soil cadmium in soils low in organic matter with a pH about 7 was the same in soils treated with 0.4 t/ha superphosphate each year

Research to identify problems

Reviews of constraints to food production in many developing countries have ranked nutrient depletion, deficiency or inappropriate timing as the most important problems followed by soil erosion and degradation and water scarcity. Nutrient shortages are a major constraint on about 60% of soils in S.E. Asia whilst all sub-Saharan African countries have negative nutrient balances, i.e. nutrient removal from soil exceeds application. In thirteen Asian countries low soil fertility and imbalances in nutrient applications are the cause of the most common environmental problems in land and water management. A general overview has revealed a variety of physical and chemical soil related constraints to productivity in S.E. Asia. These include physical limitations like a high proportion of coarse particles in the soil matrix and hence low moisture retention. If this implies a low yield potential application of nutrients should be limited unless irrigation is an option.

Chemical constraints include soils with reduced P availability because it is fixed very strongly; soils with small reserves of K; soils which lack the ability to retain nutrients; and many soils with aluminium and iron toxicity problems resulting from high acidity. The most extensive nutrient deficiencies are usually nitrogen, phosphorus and potassium but highly leached soils also frequently lack calcium and magnesium. Solutions to such problems will not necessarily be the same as those which have proved effective in developed countries in temperate climates. If food production is to be maintained and increased in different regions of the world, efficient, appropriate and economical manuring policies must be identified and applied so that environment-friendly production can be sustained.

them». Then, and even more now, there is a need for all involved to work in partnership to ensure that food is produced in ways that are financially viable, environmentally acceptable and based on concepts that will ensure the sustainability of production. Such concepts should include the maintenance of soil fertility, and the production of crops with the maximum efficiency of inputs. If these concepts are acceptable, agriculturalists must become more involved in the current debates on nutrient losses which are being dominated by those with environmental priorities who may be paying too little regard to the world's increasing need for food. Recent valuable work has been the application of modern technology, such as Global Positioning Systems, to further improve the site-specific management of nutrients and other inputs.

It is essential to continue to grow good, wholesome crops at affordable prices to feed an increasing world population.



Towards the 2000s

Population is going to continue to increase, especially in the poorer nations with fragile ecosystems. This will put a major strain on both resources and the environment. The 1994 Inter-Governmental Conference in Cairo on world population testified to an increasing awareness of such problems. However, there are religious and ethnic considerations which can make it difficult to provide acceptable standards of living and sufficient food. Agricultural research and development has a major role to play in devising techniques and strategies that ensure the sustainability of food production. These must be appropriate to local soil and climate conditions and minimize any adverse environmental effects.

As early as 1909 it was written that «The future, too, lies in intensive farming; every year the ratio of the cultivable land to the population of the world shrinks, every year science puts fresh resources in the hands of the farmer intensive farming implies the use of fertilizers; still more, it implies, or should imply, skill and knowledge in using

Balanced fertilization

The idea of balanced fertilization is not very new. In the early 1840s Liebig, a German chemist, defined the principle of the 'limiting nutrient' which made clear the need to provide plants with the correct balance of nutrients, as a deficiency in any one could limit growth and leave others unutilized. As he developed his concept of plant nutrition he hypothesized that it was only necessary to apply nutrients in the exact amount removed by the harvested crop. Experiments prove this to be incorrect because, at that time, as in many developing countries today, soils were very poor in nutrients and it was necessary to add more than was removed in the crop. It is interesting that Liebig's ideas of 150 years ago are now applicable in the developed countries where the stock of plant nutrients has been built up in the soil by past manuring.

Nowadays discussion is centred on two definitions of balanced fertilization, each of which could have very different implications for fertilizer use and crop production. An existing definition in the scien-

tific literature envisages balanced fertilization as the supplementation of the nutrient supplies in soil so that when the supply from both sources is combined, nutrients are available to crops in about the correct «physiological» ratio for optimum growth. In some cases this idea has been developed further so that having decided the correct ratio, the amounts to be applied are adjusted to achieve a target yield. The main problem with this approach is that it assumes that the available nutrient supplies in soil can be estimated with reasonable accuracy and that all of the added nutrients will become available to the growing crop in the season in which they are applied. Neither is true.

Another definition of balanced fertilization has been developed by a number of environmental organizations. Their definition implies that the amount of nutrients applied should not exceed the quantity removed in the harvested crop. Such a definition could prove very damaging. It fails to recognize the difference between the P and K aspects of soil fertility, and the role of nitrogen in crop productivity. Limiting the application of P and K to the amounts removed in the harvested crop is acceptable on soils above the appropriate critical values for readily soluble P and K in soil. But on soils below the critical values, farmers should have the option of applying more P and K than is removed in crops, to improve the fertility and productivity of their soils. Applying the concept of only applying N equivalent to that in harvested crops fails to acknowledge the immobilization of some applied N in soil organic matter and the inevitable losses by denitrification, and perhaps as ammonia, from the standing crop before harvest.

Nutrient management

Nutrient management is a much more realistic and useful approach to fertilizer use. The term implies managing all nutrient sources, fertilizers, organic manures, waste materials suitable for recycling nutrients, soil reserves, biological nitrogen fixation and bio-fertilizers, etc, in such a way that yield is not knowingly jeopardized whilst every effort is made to minimize losses to the environment. Nutrient management is readily incorporated into the concepts for the maintenance of soil fertility and crop productivity.

The maintenance of soil fertility requires the identification of those soils where nutrients like phosphorus (P) and potassium (K) can safely be accumulated in plant available forms. Critical values for each nutrient should then be determined below which there will be an unacceptable loss of yield which could jeopardize the economic viability of a farming enterprise. Agronomic advice should actively promote the build up of nutrients in soils from below the critical value to just above it. Once safely above the critical value it is, however, unrealistic to suggest that a farmer spends money on further accumulation of nutrients. The policy should merely be to replace the nutrients removed in the crop thereby maintaining soil nutrient levels. Such a policy requires regular analysis of soils to check that critical values are not being breached. Additionally, plant tissue analysis can also be used as a check

to ensure that there is no nutrient deficiency in a crop.

The environmental benefits of such best management practices include decreasing the risk of phosphorus losses to water as discussed previously. In those soils where plant-available nutrient reserves cannot be accumulated, for reasons discussed above, techniques for improving the efficiency with which annual applications of phosphorus and potassium are used must be applied. These may include the well researched benefits of placement near the seed though this involves a greater investment in machinery and management skill.

Research will also be necessary to maximize the efficiency with which nutrient inputs are used. For example, improvements in the prediction of nitrogen fertilizer need must be actively sought and tested. The excessive use of nitrogen fertilizers should be discouraged.

Consensus and cooperation

If the concepts and ideas discussed above are agreed they must still be promoted to farmers, politicians, policy makers and the public. The penalties of failing to reach a consensus are considerable for both environmentalists and agriculturalists.

The danger for environmentalists, in the face of the food requirements of an increasing world population, is that they will be seen to be putting their concerns above essential human needs. For their part, agriculturalists, seeking to increase production, would be foolish to ignore evidence of any practices that cause environmental damage which could be avoided.

To ensure the long term sustainability of the environment and food production systems, it is essential that all those involved work together to arrive at the best solutions. Perhaps the greatest challenge is the need to increase the per capita production of the world's staple cereal grains, wheat, maize, and rice which has remained constant in the last ten years. This must be a cause for concern. If future generations are to be adequately fed, the fertility and quality of soils must be maintained and where appropriate enhanced. Soils are a vital and scarce resource and mismanaging them represents one of the greatest threats to our environment and to the future of humankind.

Jonathan Swift 1667-1745
Gulliver's Travels

«He gave it for his opinion, that
whoever could make two ears
of corn or two blades of grass
to grow upon a spot of ground
when only one grew before,
would deserve better of
mankind, and more essential
service to his country, than
the whole race of politicians put
together».



*For further information contact : Jack Whelan
IFA 28 rue Marbeuf - 75008 PARIS Tel : (1) 42.25.27.07
Telefax : (1) 42.25.24.08*