A rock and a hard place

Peak phosphorus and the threat to our food security

Soil Association

Executive summary

The approaching 'perfect storm' of climate change, resource depletion, diet-related ill health and population growth is forcing us all to think again about how we produce and consume food

Yet, there is one critical issue in securing our future food security that is missing from the global policy agenda: we are facing the end of cheap and readily-available phosphate fertiliser on which intensive agriculture is totally dependent. The supply of phosphorus from mined phosphate rock could 'peak' as soon as 2033, after which this non-renewable resource will become increasingly scarce and expensive.

We are completely unprepared to deal with the shortages in phosphorus inputs, the drop in production and the hike in food prices that will follow. Without fertilization from phosphorus it has been estimated that wheat yields could fall from nine tonnes a hectare in 2000 to four tonnes a hectare in 2100. The current price of phosphate rock is approximately twice that of 2006. When demand for phosphate fertiliser outstripped supply in 2007/08, the price of rock phosphate rose 800%. This may well be a taste of things to come.

In Europe we are dependent on imports of rock phosphate, having no deposits of our own, but the geographical concentration of reserves adds further uncertainty to the future security of our sources. In 2009, 158 million metric tonnes of phosphate rock were mined worldwide. 67% of this resource was mined in just three countries – China (35%), the USA (17%) and Morocco and Western Sahara (15%). China has now restricted, and the USA has stopped, exports of phosphate.

There are serious environmental impacts of phosphate fertiliser production and use including the production of toxic and radioactive waste, cadmium pollution to soils, greenhouse gas emissions, and the eutrophication of rivers.

In the UK, and internationally, there has been no serious discussion of, or action on, what peak phosphorus means for food security. A radical rethink of how we farm, what we eat and how we deal with human excreta, so that adequate phosphorus levels can be maintained for crop production without reliance on mined phosphate, is crucial for ensuring our future food supplies. In this report we set out the actions we need to take to close the loop on the phosphorus cycle to address future shortages and prevent further environmental damage from phosphate pollution.

WHAT ACTION IS NEEDED?

Changing how we farm

- ▶ Farming systems vary as to the extent of their reliance on mined phosphate inputs for producing artificial fertilisers for use on grazing land and crops, and as additives in animal feed.
- ▶ Organic farming systems already make use of many practices to reduce the need for mineral phosphate, including managing nutrient loss; using farmyard manure, crop residues and green waste composts as fertilisers; increasing the availability of phosphorus to plants by encouraging micro-organisms and mycorrizal funghi; and using crops with high uptake efficiency.

Changing what we eat

- ▶ The benefits of reducing the amount of meat in our diets in terms of health benefits and reducing greenhouse gas emissions are commonly known, but switching to a diet with less meat can also reduce demand for mined phosphate. This is because the efficiency with which phosphorus inputs are converted to dietary phosphorus is much higher in vegetable-based products than livestock products.
- ▶ Of course different types of meat have different levels of mined phosphate demand depending on the farming system used to produce them. Meat from livestock grazed on grassland that has not been fertilised with artificial fertilisers, will perform much better than meat from livestock grazed on fields that have been, or livestock fed on grain grown using artificial fertilisers.
- ▶ Eating organic food can reduce our dependence on mined phosphate as organic farmers cannot use soluble phosphorus fertiliser, use little or no mined phosphates, and make use of practices to improve the efficiency of the use of phosphorus available in the soil, and its re-cycling within the farming system.

Changing how we deal with human excreta

- ▶ A significant proportion of phosphorus is lost from human excreta. It is estimated that only 10% of the three million tonnes of phosphorus excreted by the global human population each year are returned to agricultural soils.
- ▶ In the UK, the majority of treated sewage sludge (biosolids) is returned to land. At the present time, EU organic regulations prohibit the use of such biosolids on organic farmland due to historical concerns about the toxic effects of heavy metals, caused by combining human excreta with industrial effluent, domestic grey-water, and surface run-off. Heavy metal levels have declined in recent years, and are now low enough for the organic movement to re-consider allowing treated sewage sludge to be used where it meets strict standards.
- ▶ In the longer term on a global scale, the majority of human excreta will need to be returned to a large proportion of agricultural soils to close the phosphorus loop. It will all need to be of a high quality to protect human health and avoid environmental damage. This will require more fundamental changes to our sanitation systems. We need to start thinking of human excreta as a resource, not a waste.
- ▶ Ecological sanitation (ES) systems collect and treat wastewater flows separately, optimising their potential for re-use in agriculture, whilst minimising hygienic risk. They can reduce the risk from potential contamination from heavy metals and organic contaminants and can also reduce the high water and energy use of, and pollution caused by, the current "flush-and-forget" system that dominates in the developed world. Examples include urine-diverting toilets, high-tech vacuum systems, and composting toilets.

UK POLICY RECOMMENDATIONS

- ▶ Amendments should be made to EU regulation No. 889/2008 to permit the use of sewage sludge on organic certified land subject to certain quality criteria and appropriate restrictions, including maximum concentrations of heavy metal and organic contaminants.
- ▶ Support for research and development for organic and agro-ecological systems, as recommended by the IAASTD (2008) report, to include improving the efficiency of phosphorus use.
- ▶ A shift towards ecological sanitation (ES) in the UK is clearly a long-term goal involving significant infrastructure development in urban areas that are largely dependent on centralised sewage systems. However, there are many areas where infrastructure changes would be more straightforward:
  - ▶ ES could be made mandatory for all new housing developments.
  - ▶ incentives and support could be provided for retro-fitting with ES where appropriate, for example in rural areas where houses are not connected to centralised sewage systems and access to agricultural land would be easiest. This would be particularly useful on small-holdings and farms.
  - ▶ installing ES in public toilets and public buildings would also be excellent steps forward.
- ▶ Support for public health policies that promote diets that are both healthy and climate-friendly, and reduce demand for phosphate – much less meat and dairy products (but proportionally more from grass-reared livestock) and more seasonal fruit and vegetables, starchy carbohydrates and whole grains.

Why is phosphorus so vital for our food security?

Phosphorus is an essential nutrient for all plants and animals. It forms part of genetic material, and is used for energy transfer, within the cells of living things[1] – and our supply of phosphorus from mined phosphate rock could 'peak' as soon as 2033[2]

An adequate supply of phosphorus to plants is essential for seed formation, root development and the maturing of crops.[3] It is second only to nitrogen as the most limiting element for plant growth[4] and it cannot be substituted in food production.

The amount of phosphorus that is found naturally in soils varies greatly and can range from around 500 to 2500kg per hectare. However, only a small proportion of this phosphorus will be in the right form (soluble organophosphates in the soil solution) for it to be available for plants to take up, indeed this is often less than 10g per hectare. The majority of the phosphorus is stored in the soil in insoluble forms (mineral and organic) that are not readily available to plants. As they grown, plants take up the available phosphorus and deplete the soluble pool. This can be replenished by the conversion of the insoluble phosphorus through chemical transformations in the soil and microbial activity[5] – if there is enough stored in the soils.

Under natural conditions the phosphorus taken up by growing plants is returned to soils in plant residues, and from the urine, excrement and carcasses of the animals that have grazed the vegetation. In cultivated systems some of the phosphorus taken up by the crop is removed in harvest, and then eaten directly by humans or fed to livestock. Therefore it is necessary for phosphorus to be returned to the soil, in a form that is immediately available to plants, or to be stored for later release (as well as making sure that phosphorus reserves are converted to a soluble form as efficiently as possible).

Historically, phosphorus was returned to agricultural land through the application of animal manure and human excreta. However, from the mid nineteenth century, the use of this local organic matter was replaced by phosphate mined in distant places, briefly in the form of guano, bird droppings deposited over thousand of years, but much more significantly mined rock rich in phosphate.[6] In parallel, as Lady Eve Balfour alludes to,[7] the introduction into urban areas of flush toilets meant that human excreta was no longer returned to the soil, but washed out into water systems.

"...When water-borne sewage was introduced into our cities, the capital of the soil – its fertility – which is removed from it year by year in the form of crops and livestock, no longer found its way back to the land in the form of the waste products of the community, but was poured into the sea or otherwise destroyed."
The Living Soil, Lady Eve Balfour, 1943

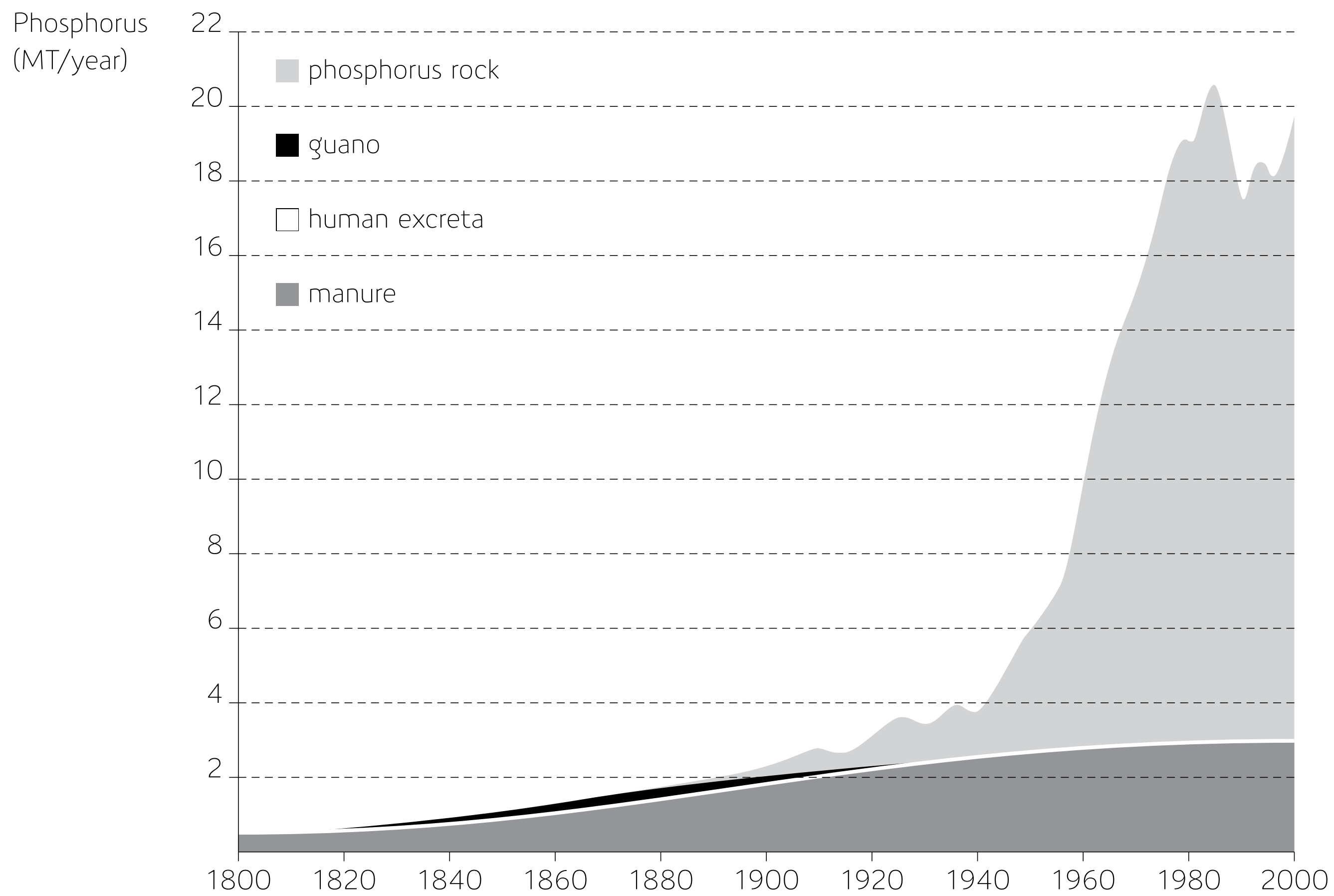
By the late nineteenth century, processed mineral phosphorus fertiliser from phosphate rock was routinely used in Europe and its use grew substantially in the twentieth century.[8] Figures from the US geological survey show that production of phosphate rock increased from approximately three million tonnes in 1900, to 41 million by 1960 and reaching current levels of around 150 million by 1980.[9]

Today, non-organic agriculture is dependent on regular inputs of phosphate fertilisers,[10] derived from rock phosphate, to replenish the phosphorus lost from the soil in the process of growing and harvesting crops, and to maintain high yields. In 2009 phosphate fertiliser application on non-organic farms in the UK was on average 23kg per hectare on tillage crops and 9kg per hectare on grassland.[11]

Crops used in non-organic systems have been bred to rely on high levels of artificial fertilisers to give high yields. Without fertilisation from phosphorus it has been estimated that wheat yields could fall from nine tonnes a hectare in 2000 to four tonnes a hectare in 2100.[12] Thus, the availability and costs of phosphorus is one of the key factors that will limit crop yields in the future. As Cordell *et al* argue,[13] it seems that "we are effectively addicted to phosphate rock".

Figure 1

HISTORICAL GLOBAL SOURCES OF FERTILISERS (1800–2000)[14]



When is 'peak phosphorus' due?

Whilst many people are now familiar with the reality of 'peak oil', there is much less awareness that rock phosphate is also a non-renewable resource and that the supply is also expected to 'peak' in the near future

Phosphorus (P)[15] is a key input into artificial fertilisers along with nitrogen (N) and potassium (K).[16] Whilst nitrogen can be obtained biologically from the air, and supplies of potassium are far larger,[17] it will be phosphorus that will be the bottleneck for future productivity in our agricultural systems.[18]

As Hubert (1956)[19] first highlighted in relation to peak oil, it is not when a resource is completely gone that problems arise, but when the high quality, highly accessible reserves have been depleted. This is the point at which production reaches its maximum (its peak) and afterwards the quality of the remaining reserves is lower, they are harder to access and thus increasingly uneconomical to mine. Supply then declines and price rapidly increases.[20]

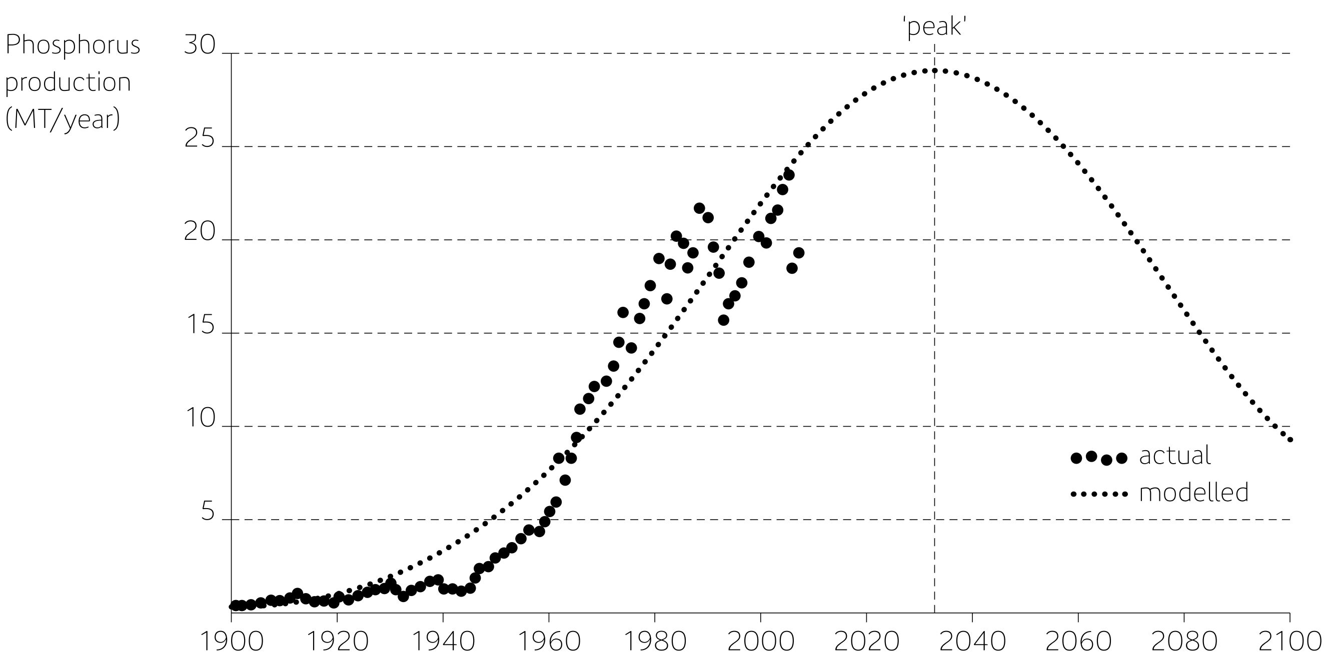
There is a growing consensus on the reality of peak phosphorus, although the exact year is of course not known[21] as it depends on a variety of supply and demand-side factors where there is uncertainty over future trends.[22] However, Cordell *et al*[23] suggest that the peak in global phosphorus production could occur by 2033.

While a recent report from the International Fertiliser Development Centre (IFDC) suggests world phosphate rock reserves may be greater than estimated by USGS,[24] this would only shift the peak timeline a few decades – it would not change the underlying fundamental problem of phosphorus scarcity,[25] nor reduce the likelihood of continuing steep rises in the price of phosphate fertiliser.

Figure 2

INDICATIVE PEAK PHOSPHORUS CURVE[26]

Illustrating that, in a similar way to oil, global phosphorus reserves are also likely to peak after which production will be significantly reduced



Unsustainable supply

Our current system of mining, using and disposing of phosphorus is not only going to be impossible when phosphate supplies 'peak', but is unsustainable in its current form for a number of other reasons

GEOPOLITICAL REALITIES OF PHOSPHATE ROCK SUPPLY

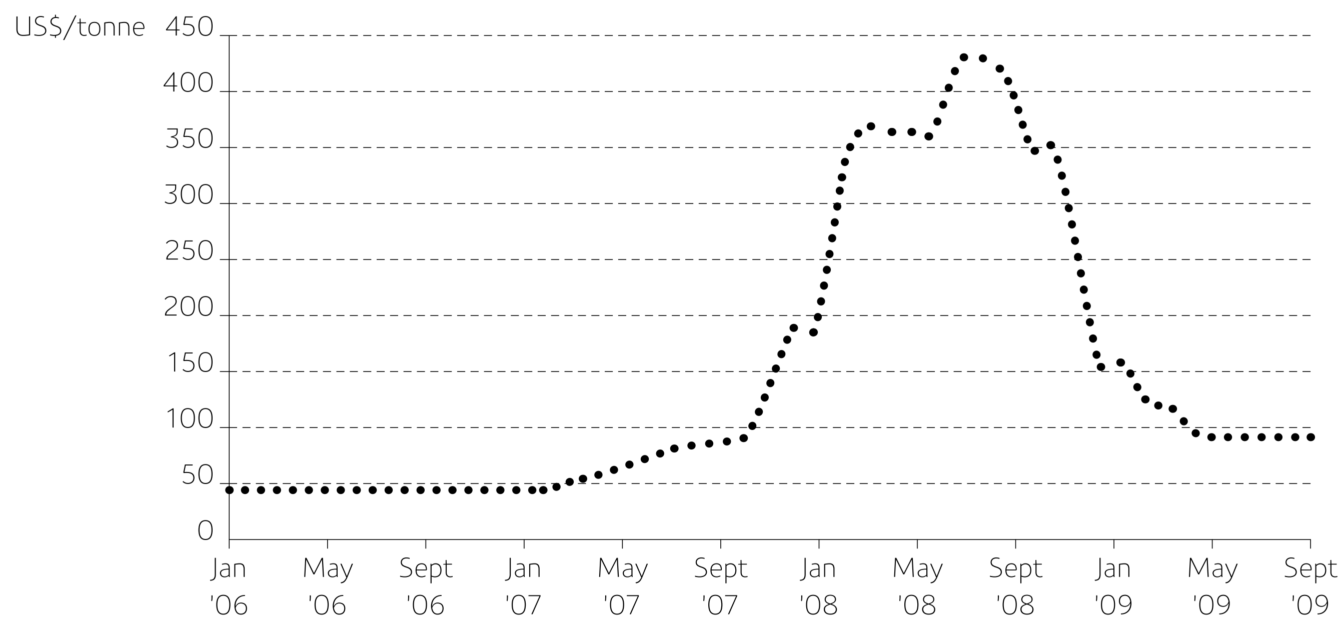
The geopolitical realities of the sources of phosphate rock, which are highly geographically concentrated, add a further level of uncertainty in securing future phosphate supplies. In 2009, according to the US Geological survey, 158 million metric tones of phosphate rock were mined worldwide. 67% of this resource was mined in just three countries – China (35%), the USA (17%) and Western Sahara (Morocco) (15%).[27] For known reserves,[28] 87% are found in just five countries. By far the biggest is in the Western Sahara and Morocco (35%) followed by China, (23%), Jordan (9%), South Africa (9%) and the USA (7%).[29] The uneven distribution of reserves led to an article in Scientific American to declare phosphorus "a geostrategic ticking time bomb".[30]

In Europe we are dependent on imports, having no deposits of our own. China has already begun to safeguard its own supplies by imposing a 135% tariff on exports from 2008.[31] The USA stopped exporting any phosphate rock in 2004 and since the early 1990s has significantly increased the quantity it imports,[32] with all its imports since 2005 coming from Morocco.[33] It is estimated that the USA only has 20-25 years of reserves remaining.[34] Some of Morocco's phosphate reserves are located in the Western Sahara, a territory that is internationally recognized as a sovereign country, but which has been effectively occupied by Morocco since 1975. In 2004 the US signed a bilateral free-trade agreement with Morocco that allows the US long-term access to its phosphate.[35] Some companies in Scandinavia, on the other hand, have halted imports

Figure 3

PHOSPHATE ROCK COMMODITY PRICE (MOROCCO)[36]

Increased 800% between January 2007 and September 2008



Unsustainable supply

of Moroccan phosphate in protest against its occupation of Western Sahara.[37]

PRICE VOLATILTY IN THE GLOBAL MARKET

In 2007/08, the phosphate rock commodity price increased by 800% (see figure 3, page 7). This has been attributed to increases in the price of oil;[38] increased demand for fertilisers due to the increase in biofuels and the expansion of meat and dairy-based diets, and a lack of short-term supply capacity to produce enough phosphate rock to meet demand. As a result of the price spike, farmers around the world were holding back purchasing fertilisers, which partly caused the price to drop again.[39] This is perhaps a taster of things to come. The current price is approximately twice that of 2006.[40]

In the UK prices for phosphate fertiliser (triple super phosphate) are currently about £310–£320 per tonne (on-farm) but are predicted to increase in the near future reflecting increases in demand in the global market.[41]

ENVIRONMENTAL IMPACTS

Most fertiliser is produced by dissolving phosphate rock in sulphuric acid to produce phosphoric acid. For each tonne of phosphate processed in this way, five tonnes of a by-product, phosphogypsum, is produced, and due to the presence of naturally occurring uranium and radium in the phosphate ore this is toxic and radioactive.[42] There is serious concern about environmental damage and operator exposure as a consequence of radiation issues, phosphogypsum waste stacks, heavy metal and wastewater issues and fluoride emissions.[43] Cadmium inputs to soil from rock phosphate fertiliser production has also been a concern with long-term implications for soil fertility and human health.[44]

Greenhouse gas emissions are another consideration. The mining, production and trade of artificial fertilisers is dependent on cheap oil supplies. The mining of fertiliser ores and the production of fertilisers by chemical solubilisation and concentration is a very energy intensive process. As an internationally traded commodity, 30 million tonnes of phosphate rock was exported from the country where it was mined in 2008,[45] emissions (and pollution) from transport are also significant.

There are further environmental consequences once phosphate has been used. Because top soil is usually relatively high in phosphorus, significant losses of phosphorus from soils can occur by wind or water erosion. Phosphorus bound to soil particles can enter watercourses. Smaller amounts of phosphorus are lost to water through leaching, as the amount of soluble phosphorus in the soil solution is usually very small,[46] but this can happen when there are high levels of accumulated phosphorus.

The process of eutrophication, the enrichment of water by nutrients, is primarily caused by phosphorus in rivers and other fresh-waters. Eutrophication can lead to algae growth, disrupting normal ecosystem function by using up all the oxygen in water, and causing the death of other aquatic species, and affecting water quality. The source of the phosphorus, whether it is sewerage or from agriculture, varies from catchment to catchment.[47]

What policies are in place?

Whilst the previous UK government recognised that phosphorus is the key nutrient causing eutrophication in rivers and other freshwaters,[48] the issue of peak phosphorus has been missing from all significant government policy statements on food policy and food security in the UK until recently[49]

However, the January 2010 (updated) version of UK Food Security Assessment[50] included a new indicator on phosphate rock reserves. The inclusion of this indicator is in itself welcome. The report recognises that phosphate rock is a geologically finite resource, and in the long-term at least, it is recognised that ways to recycle phosphate in a more efficient way would be needed. Surprisingly though there is little sense of urgency, rather a positive outlook for the next five to ten years is presented. In the short to medium term, the argument is made for the life of this finite resource to be extended through technology that can improve efficiency and thus decrease costs and by exploring new offshore deposits such as those in the Pacific and Atlantic.

Indeed, it has been suggested by some scientists that market forces will lead to new technological developments emerging that will improve the efficiency of phosphate rock extraction and that off-shore and low grade deposits will become economically viable once all high-grade reserves have been depleted.[51] This may be true in the shorter term, but we should take heed at what is happening with oil; as it has got scarcer and more expensive to produce, so called 'non-conventional' resources, such as tar sands and shale oil, have become economic – with devastating environmental consequences.[52] And of course the price of oil has increased.

Another indication that concern about phosphorus supplies may be beginning to reach the ears of policy makers came in one of the first comments on the future of farming from the new Coalition Government's Secretary of State for the Environment, Food and Rural Affairs when she argued that "...recent months have highlighted another trend which the industry needs to anticipate – the rush to stake claims in the mineral resources our modern food production and supply chains need to function. The value and scarcity of many of these resources is not lost on those countries lucky enough to have them... Supplies of phosphate, often credited with making the 1960s Green Revolution possible, and other rare earth metals are increasingly being guarded by the countries they came from." This is the first time a UK government minister has acknowledged the possibility of any problems with the future supply of phosphates to UK agriculture.[53]

At the international level, there are several FAO research reports mentioning the issue of phosphate scarcity,[54] yet there has been no real action or discussion of the issue within the international debates on global food security.[55] It has not been mentioned in the any of the recent high level reports on food security, although a paper written in preparation for the FAO expert meeting on how to feed the world in 2050 does acknowledges that phosphorus is a major non-renewable resource where scarcity could significantly affect crop yields by 2050.[56]

How we farm

Different farming systems vary as to the extent of their reliance on mined phosphate inputs for producing artificial fertilisers for using on grazing land and crops, and additives in animal feed (see next section 'What we eat'.)

Agricultural systems can be changed in other ways to improve phosphorus use efficiency, and these are set out below.

MANAGING NUTRIENT LOSS

Only a small percentage (15–25%) of the phosphorus added to the soil in the form of artificial phosphate fertiliser and manure will be used by the plants in the year of application. The rest can be stored in the soil in insoluble forms, to be used later when the soluble forms are used up by the crops. However, soils differ in their ability to store phosphorus in an insoluble form. A soil cannot hold increasing amounts of phosphate in the insoluble phase without also increasing soil solution phosphate – this increases the risk that phosphate will be lost via soil runoff or leaching through the soil.[57]

In attempts to reduce phosphate pollution, in the UK there are now guidelines to farmers on how they can reduce phosphorus loss from their farms through, for example, following a nutrient management plan to ensure efficient use of fertilisers and organic manures, not spreading organic manures in conditions that are likely to lead to run-off, controlling soil erosion and run-off and matching the phosphorus content of feed to the needs of the livestock.[58]

BETTER RECYCLING OF FARM WASTE

Phosphorus can be returned to the soil through the application of livestock waste (farmyard manure and slurry), as well as crop residues and other composted plant material.

Typical phosphate levels of solid farmyard manure (FYM) from conventional systems have been estimated as 3.5kg/t of phosphate for cattle FYM, pig FYM 7kg/t, sheep FYM 2kg/t, poultry layer manure 13kg/t and litter from laying hens 25kg/t. The short-term availability of phosphorus from animal manures is greater than from rock sources.[59] Compost made from garden and food waste typically contains 3kg/t of phosphorus. Approximately, 15% of the phosphorus in compost will be available to the crop grown in the first year.[60]

INCREASING AVAILABILITY

As previously stated, the total phosphorus content of soils varies greatly, ranging from around 500 to 2500kg per hectare. In comparison, often less than 10g per hectare of phosphorus is in the soil solution in a soluble form (which plants can take up) at any one time.[61] The ability of the soil to maintain a pool of phosphorus in a soluble form that is available to plants can be encouraged in a number of ways and steps can be taken to use crops that make the most efficient use of available phosphorus:

▶ Encouraging micro-organisms
Phosphorus stored in an organic form is made available to plants by the activity of micro-organisms such as bacteria and fungi which use enzymes to mineralise the organic phosphorus. Some soil micro-organisms also excrete organic acids which are able to attack calcium phosphates and hence release the phosphorus. The regular return of crop residues and the addition of composts and manures will stimulate biological activity and increase the amounts of phosphorus cycling.[62]

▶ Using crops with high uptake efficiency
The efficiency of phosphorus use in rotations could be increased by the targeted inclusion of crops and/or cultivars with high phosphorus efficiency.[63] Plants have adapted several ways of surviving and thriving in low phosphorus soils. Phosphate only moves very slowly in soils, and so root length and distribution is very important in determining how much phosphorus is available to plants. Plants can increase their root surface area through having more or longer roots and by developing increased numbers of root hair cells. Maintaining good soil structure to encourage rapid root development, particularly ensuring that root growth is not impeded by compaction, is important in improving phosphorus utilisation.[64]

Some crops have particularly deep rooting systems, such as chicory, clover and lucerne, and including these crops in a rotation can help to mine phosphorus from deeper in the soil.[65] Current crop breeding programmes tend to use soils with high levels of phosphorus availability so varieties with increased phosphorus use efficiency are not often identified. Breeding crops that acquire and/or use phosphorus more efficiently is one strategy to reduce the use of phosphate fertilisers.[66]

Some crops have specially adapted root structures, for example, cluster roots in lupin, which release chemicals, (such as organic acids or acid phosphatase) that are able to act on insoluble phosphorus in the soil and make it more available where the plant needs it.[67] Crops can therefore be included in the rotation because of their ability to make phosphorus available in a soluble form; there is some evidence the buck-wheat is particularly effective at releasing phosphorus from additions of phosphate rock and making the phosphorus more available for subsequent crops.[68]

▶ Mycorrhizal fungi
Most plants (except those from the Brassicae and Chenopodiaceae plant families) form associations with arbuscular mycorrhizal fungi. The fungi act as a bridge between plant cells and the soil and substantially increase the effective root-soil contact area. For example it is these associations that enable leek, which has very few roots, to access enough phosphorus to thrive.[69] Soils with high levels of available phosphorus limit the extent to which mycorrhizal assocations forms and function effectively. Designing crop rotations for the fungi-plant associations is possible through minimising fallows and ensuring that suitable host crops for the fungi are present. In the past rotations have largely been designed to optimise access to nitrogen, in the future choosing crops with a variety of mechanisms to optimise phosphorus efficiency may well be equally important.

ORGANIC AGRICULTURE

Organic farming systems already make use of these practices in order to reduce the need for mineral phosphate. In organic systems, the goal is for sufficient phosphorus to be returned to the soil through the application of farmyard manure (FYM), slurry and greenwaste composts from organic farming sources. Management of livestock manures and crop residues should aim to achieve maximum recycling of nutrients with minimum losses. The maintenance of ground cover can also reduce the loss of phosphorus.[70] Organic farmers should also monitor their soil nutrients and manage them in ways that encourage the soil to release more phosphorus into the form available to crops through promoting biological activity, improving soil structure, maintaining the right soil pH, and using green manures and balanced crop rotations.[71]

One of the key principles of organic agriculture is that fertility should be built up through biological cycles, but this is much more difficult for phosphorus (and potassium) than it is for nitrogen.[72] Nearly all organic farms will need some input of phosphorus from off the farm at some point, and ideally this should involve the return of phosphorous that left the farm in crops, milk and meat by recycling the phosphorous in human excreta. Some organic livestock units bring in considerable quantities in purchased feed. Whilst the use of soluble phosphorus fertilisers (for example, triple super-

How we farm

phosphate) is prohibited in organic farming, under Soil Association and other organic standards, natural rock phosphate can be used with justification[73] (such as a soil analysis showing a low level of phosphorus). Generally, it would be used to ensure that the rotation has balanced inputs and outputs of phosphorus; because it is a slow release source it is usually applied once in a rotation (every five to seven years). However, mineral fertilisers must be regarded as a supplement to, and not as replacements for nutrient recycling within the organic farm.

What we eat

By changing what we eat we can reduce demand for mined phosphate

As indicated earlier, eating organic food can reduce our dependence on mined phosphate as organic farmers cannot use artificial fertiliser, and make use of practices to improve the efficiency of the use of available phosphorus, and its re-cycling within the farming system.

The benefits of reducing the amount of meat in our diets in terms of health benefits and reducing greenhouse gas emissions are commonly known, but switching to a diet with less meat and dairy products can also reduce the amount of mined phosphate needed. Under current farming systems, it has been estimated that an average non-organic, vegetarian diet requires substantially less phosphate rock than a meat-based diet: For the vegetarian diet 0.6 kg phosphorus a year (or 4.2 kg of phosphate rock), whilst a meat-based diet requires 1.6 kg phosphorus a year (or 11.8 kg of phosphate rock).[74] This is because the efficiency with which phosphorus inputs are converted to dietary phosphorus is much higher in vegetable-based products than livestock products.

For example, in the case of the Australian food system the production of 22 Kt of dietary phosphorus in meat and dairy products requires an input of 231 Kt of phosphorus in the form of animal feed, fertiliser and feed supplements. This gives a conversion ratio of 10. By comparison, the production of 60 Kt of phosphorus in vegetable products requires an input of 241 Kt of phosphorus (from fertiliser), and thus has a much lower conversion ratio of four.[75]

Of course different types of meat have different levels of mined phosphate demand depending on the farming system used to produce them; the amounts required for producing animal feed, fertilising grass-land and as feed supplements. Meat from livestock grazed on grassland that has not been fertilised with artificial fertilisers, will perform much better than meat from livestock grazed on fields that have been, or livestock fed on grain fertilised by artificial fertilisers. Grazing animals also perform better because of the use of animal feed supplements: about 7% of mined phosphate goes to produce additives for animal feed for non-ruminants (poultry and pigs).[76] Much of the phosphorus in most cereals and leguminous grains is organically bound in phytic acid and is therefore almost indigestible for non-ruminants that lack the correct enzyme (phytase) to free the phosphate. This means that inorganic phosphorus is added to animal diets, and contributes the large amounts of phosphorus in animal manure.[77]

At the global level, the relative inefficiency of a meat-based diet can be understood in the context of the shift away from mixed-farming with the effect that a significant proportion of animal manure is not returned to arable land. Thus, it has been estimated that globally nearly half of the phosphorus in animal manure is lost into landfill, water courses or onto non-arable land.[78]

How we deal with our waste

Whilst a change in diets, and a shift to organic farming systems are important in order to reduce our dependence on mined phosphate, to close the phosphorus loop we will need to return not only all animal waste to the soil, but other types of waste as well

Composting food waste from households, food processing plants and food retailers are all ways that phosphorus can be recovered and recycled.[79] However, recycling the majority of human excreta will also be necessary.

It is estimated that of the three million tonnes of phosphorus excreted by the global human population each year, only 10% are returned to arable soils as wastewater or excreta. 1.2 million tonnes are lost (for example as sludge in landfill) whilst 1.5 million tonnes enter inland or coastal waters as treated or untreated sewage.[80]

In the UK, as in most of the developed world sanitation is based on the flush toilet – the 'flush and discharge' model where human excreta is disposed off through a water-based sewage system that was originally built to protect public health: In the 1850s during a severe cholera epidemic in London, John Snow isolated the disease vector to a water pump near raw sewage and a large-scale implementation of sewerage systems across cities in the developed world followed. Pathogenic excreta were flushed away from cities using water. This 'sanitation revolution' was hailed by the *British Medical Journal* as the biggest medical advance since 1840.[81]

Today in the UK, human excreta is combined with other domestic wastes (grey water from washing), industrial effluents and surface run-off and enters a sewage treatment works (STW). It contains a significant amount of phosphorus and it is estimated that about 85% of the phosphorus in wastewater entering a STW originates from household waste (dietary sources 60% and detergents 25%). Waste from industrial sources that is also treated at STWs makes up the remaining 15%.[82] Once treated this effluent enters the waterways, but it still contains phosphorus and in one estimation about 65% of the phosphorus in UK waters is from STWs, with another 25% direct from agricultural run-off.[83] In other studies the contribution from agriculture has been higher, and it is clear that agriculture and sewerage run off contribute different proportions in different catchment areas.[84]

The EU Urban Wastewater Treatment (UWWT) Directive (implemented in the UK through the UWWT Regulations 1994) regulates the collection and treatment of wastewater from domestic and industrial sources. It identifies sensitive areas such as eutrophic waters where nutrient loads cause problems, where extra treatment of the sewage is required.[85] In the UK this has triggered the water industry to invest in new technologies for phosphorus removal at the larger-scale sewage treatment works – at a cost of approximately £950 million.[86]

The sewage waste is dosed with chemicals in order to precipitate out the phosphorus.[87] This is then transferred to the sewage sludge, thus significantly raising the concentration of phosphorus in the sludge.[88] However, this is an expensive process and the water industry continues to spend significant amounts of money removing phosphates from wastewater, estimated to be around £35 million a year. The chemicals used to do this are usually ferric chloride or aluminium salts, which have traces of hazardous substances. It is also an energy-intensive process.[89] Once treated to meet regulatory standards, this effluent is returned to the water environment.

RECYCLING SEWAGE SLUDGE TO FARMLAND

Treated sewage sludge (biosolids) with increased levels of phosphorus, can be returned to farmland as a fertiliser after undergoing further processing by a variety of treatment methods in order to meet standards acceptable for agricultural application. It is estimated that the availability to plants of the phosphorus content of sewage sludge in the year of application is about 50%.[90] About half of the sludge produced in the UK is treated by anaerobic digestion, (where micro-organisms break down biodegradebale material in the absence of oxygen), which also produces renewable energy in the form of methane gas that is used for combined heat and power (CHP).[91]

In 2008/09, 1.7 million tonnes of dried solid sludge were produced. An average of 84.3 % of this was recycled to land, with the vast majority to agricultural land, and the rest to land reclamation and composting. The proportion of sewage sludge that is returned to agricultural land varies significantly between regions with nearly 100% in the Southwest, to about 30% in Yorkshire.[92] It has been estimated that the "the notional fertiliser replacement value of the nutrients supplied in biosolids is in the region of £20 million".[93] There is legislation and guidance governing how much and what types of sewage sludge can be used. [94]

However, biosolids were only returned to 80,000 hectares of agricultural land (2006)[95] of the total 6.2 million hectares of croppable land in the UK,[96] and it is being argued by some that the amount of sewage sludge being returned to farmland should be increased in the UK. Nevertheless, the amount that can be used is restricted by the nitrogen content of the sludge, with the strictest limits in nitrate vulnerable zones (NVZs) in order to meet the EU nitrates directive.[97] The limited availability of agricultural land in close proximity to large urban centres where the biosolids are produced, and which minimises transport costs, also restricts recycling. The available land bank is further constrained by regulations controlling the addition of heavy metals to soils.

POTENTIAL CONTAMINANTS

▶ Heavy materials

Sewage sludge results from human excreta, but also includes discharges to the sewer system from industrial effluents, animal or vegetable processing wastes and run-off of storm water from roads and other paved areas. In addition to organic waste material sludge therefore contains traces of many of the contaminating substances used in our modern society.[98] Of particular concern are heavy metals including cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn). Given that sewage sludge contains larger concentrations of heavy metals than the background values found in soil, consequently the regular application to land gradually raises the total metal content of soil in the long-term. The potential consequences include reduced plant growth (phtotoxicity) due to phytoaccumulation in plant tissues above tolerable thresholds (Zn, Cu, Ni, Cr); heavy metals entering the food chain via crop uptake (Cd) or via offal meat (Cd and Pb); animal health (Cu, Pb) and soil microbial processes (Zn).[99]

The risk of heavy metal contamination to soil, agriculture and human health posed by using sewage sludge is still debated. Estimates of the relative contribution that biosolids makes to heavy metal inputs to soil in relation to other sources (including atmospheric deposition, livestock manures and inorganic fertilisers) found that biosolids were an important source, accounting for 8% of total Zn inputs, 17% of Cu and 4% of Cd. The highest rates of heavy metal inputs on an individual field basis were from biosolids.[100]

In the UK, there are regulations controlling the maximum permitted concentrations of heavy metal in soil and also the maximum permissible average annual rate over a 10 year period[101] – to comply with EU legislation. However, the level of heavy metals in sewage sludge has declined substantially in recent years (see Table 1, page 16). This is believed to be because of effective trade effluent control measures taken by the water industry[102] (especially in the 1980s and 1990s); improved agricultural practices; restrictions on emissions, production and use of

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dangerous substances within the EU;[103] improved industrial practices and efficiency; and the changing industrial base away from traditional types of manufacturing – encouraged by earlier recessions.[104] For Professor Smith, professor of bioresource systems at Imperial College, the declining concentrations of heavy metals in contemporary sewage sludge means it no longer poses a risk to the environment or human health.[105]

Under EC Regulation No 889/2008, (that lays down the rules for the implementation for EC Reg. no. 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control) human sewage sludge is *not* one of the permitted fertilisers or soil conditioners.[106] This is because of concern over contamination of levels over heavy metals at the time when the legislation was first developed. Thus at the moment it is not permitted for biosolids to be used on organic land in Europe.

However, the recorded current concentrations of heavy metals in biosolids (average for 2001-07) are now, substantially lower than the Soil Association maximum standards for levels of heavy metals

Table 1

HEAVY METAL CONCENTRATIONS IN BIOSOLIDS IN AGRICULTURE (MG/KG DRY SOLIDS)[107]

	82/83 *	90/91 *	96/97 **	01/07 ***
Zinc	1205	889	802	636
Copper	625	473	565	330
Nickel	59	37	59	38
Cadmium	9	3.2	3.4	1.7
Lead	418	217	221	151
Mercury	3	3.2	2.3	1.4
Chromium	124	86	163	92

* median ** weighted average mean *** mean

allowed in manure.[108] Whilst these figures are only average figures for biosolids for the whole of England and Wales, over a seven year period, the lower levels, and the scope for further improvements, certainly indicates that the concentration of heavy metals is now low enough for the organic movement to reconsider the ban on the use of sewage sludge.

▶ Organic compounds

However, organic compound contaminants also pose a risk. There are 42 organic compounds (OCs) that are regularly detected in sludge including pharmaceuticals, antibiotics, endogenous hormones and synthetic steroids, detergent residues, solvents, flame retardants, compounds that leach from plastics and surfaces; chlorintated pesticides. In addition, there are persistant compounds generated by cooking food, associated with impurities in wood preservatives, and those created from the incomplete combustion of fossil fuels deposited onto paved surfaces.[109] The risk that these pose to the environment and human health is disputed: A recent review of the potential environmental and health impacts of OCs, argues "that… [OCs] do not necessarily constitute a hazard when the material is recycled to farmland" and that "recycling sewage sludge on farmland is not constrained by concentrations of OCs found in contemporary sewage sludge".

Nevertheless, the report also recommends that other issues need further investigation including: the potential significance of contamination by personal-care products (e.g. triclosan), pharmaceuticals and endocrine-disrupting compounds in sludge on soil quality and human health; the microbiological risk assessment of antibiotic-resistant micro-organisms in sewage sludge; and the impacts of chlorinated paraffins on the food chain and human health. Whilst there is currently no UK legislation on organic containments from sewage sludge, a number of European countries have set limits for the maximum concentrations of OCs in biosolids, and proposals in the EC Working Document on Sludge (2000) have been made for introducing them at the EU level.[110]

SHORT-TERM SOLUTIONS

Before the EU regulation, the Soil Association standards allowed sewage sludge use with the provisions that it was properly treated to kill pathogenic micro-organisms; the heavy metal concentrations were within strict limits, that it was only used on crops not for direct human consumption; and only used for one year in every three.[111] In addition to addressing the current situation with regard to heavy metals and organic contaminants, the organic movement needs to consider the risk of GMOs (genetically-modified organisms) being present in the sludge. As all sludge is treated before it goes on to farmland, and is largely inert, there is an argument about whether it has any value in enhancing the microbiological life of the soil.[112]

However, returning human excreta to agricultural land does reflect three of the principles of the organic movement – the law of return, a holistic or systems approach, and the use of biological and ecological processes. The critical nature of peak phosphorus justifies amendments being made to EU regulation No. 889/2008 to permit the use of sewage sludge on organic certified land where that sewage sludge meets certain quality criteria and appropriate restrictions, including maximum concentrations of heavy metal and organic contaminants within the sludge.

Additionally, in the more immediate future, further steps could be taken to further reduce the environmental impact of the sewerage system, such as the proposed consultation on phasing out the use of phosphates in detergents.[113]

Another method to reclaim phosphorus from sewage that is currently being developed is through the production of struvite, an inorganic salt [(NH4) MgPO4•6(H2O)] that can be precipitated out of some sewage sludges. It has the advantages of containing no heavy metal or organic contaminants, and can be beneficial to water companies as it can avoid the build up in STW that causes operational difficulties. Whilst research has shown that it has potential to replace chemical fertilisers on agricultural land,[114] it contains relatively low levels of nitrogen, no potassium and is not, of course, an organic fertiliser and thus contains no organic matter. In the short-term, this may offer a partial solution to phosphorus recycling from sewerage.

Towards ecological sanitation

Whilst having a sanitation system that eliminates all hygiene hazards is obviously a priority, a new approach, ecological sanitation (ES), minimises hygienic risk and protects the environment, returning nutrients to the soil, and conserving valuable water resources

It is possible to reduce the risk of potential contamination from heavy metals and organic compounds from industrial sources and domestic greywater. Contamination is reduced if sanitation service providers put in place infrastructure that does not mix human excreta with other waste streams.[115] (Although some OCs such as detergent residues and pharmaceutical residues could still be present.) There are other reasons to consider moving away from the 'flush and forget' system that dominates in the developed world. Whilst this system has played a critical role in protecting public health since its inception in the nineteenth century, it is less well suited to respond to the resource-use and environmental constraints of today. This system, which is based on the collection and transport of wastewater via a sewer system using (drinking) water as a transport system is very water and energy intensive,[116] two resources which society desperately needs to reduce our use of. In the UK, the water industry's carbon footprint is approximately five million tonnes of carbon dioxide per year.[117]

Under the ES paradigm, human excreta and water from households are recognised as a resource, and not as waste, and are made available for re-use. It is applicable in the developed world, as well as the developing, where it is estimated that 2.4 billion people do not have access to adequate sanitation services and 1.1 billion do not have access to improved water supply sources, causing serious health problems.

It has been estimated that the cost of such ES systems implemented on a global scale, could be offset by the commercial value of the phosphorus (and nitrogen) they yield.[118]

The approach encapsulates a range of technologies to be used as appropriate in different local contexts. ES provides alternative solutions with or without water, while providing containment, treatment and recycling of excreta. It can involve soil-based composting toilets in shallow reinforced pits, dry urine-diverting toilets with storage vaults, urine-diverting mini-flush toilets and even high-tech vacuum systems.[119] In practice, it relies on collecting and treating the different wastewater flows (blackwater and greywater; urine and faeces) separately to optimise their potential for re-use.[120]

The separation of urine from solid waste is key to the ES approach. Urine is essentially sterile and if it is not mixed with faecal matter in the toilet it can be stored and used safely.[121] It is estimated that it could provide more than half the phosphorus required to fertilise cereal crops.[122] The WHO has developed guidelines for the safe use of wastewater, excreta and greywater, and states that "Urine alone contains more than 50% of the phosphorus excreted by humans. Thus, the diversion and use of urine in agriculture can aid crop production and reduce the costs of and need for advanced wastewater treatment processes to remove phosphorus from the treated effluents."[123] However, it is of course essential that farmers and those working with wastewater take precautionary measures to avert associated health risks.[124]

Research has been carried out on the effects of urine as a fertiliser and there is some evidence that it is effective and can be safely used on crops.[125] In Sweden, two municipalities have mandated that all new toilets must be urine diverting. Typically, this involves a dry or flush urine diverting toilet to collect the urine, which is then piped and stored, in a simple storage tank under the house or to a communal storage tank. It is then collected by local farmers once a year for use as a liquid fertiliser.[126]

Human faeces needs to be treated to attain hygienically safe conditions: A high pH (through the addition of wood ash or lime), a long storage time and high temperatures are the critical factors affecting microbial inactivation.[127]

A new way forward

IMPLEMENTING ECOLOGICAL SANITATION SYSTEMS

This is not to understate the scale of the change needed to implement ecological sanitation (ES) systems. Indeed, it has been described that "the recycling of urine is a socio-technical progress that has no institutional or organisational home" and that a pervading "urine-blindness has prevented modern societies from tapping into this abundant source of plant nutrients in urine".[128] In the UK it will involve massive infrastructure developments given the extent to which urban areas are largely dependent on old centralised sewage systems.

However, there are now clear financial, political and legislative imperatives for the government to take the lead on this issue as the problems with the current sanitary system, such as water usage and excess nutrients, become increasingly apparent and costly to deal with.[129]

Indeed, there are many areas where infrastructure changes would be more straightforward: ES systems could be made mandatory for all new housing developments. Incentives and support could be provided for retro-fitting ES systems where appropriate for example in rural areas where houses are not connected to centralised sewage systems and access to agricultural land would be easiest. This would be particularly useful on smallholdings and farms. Installing ES systems in public toilets and public buildings would also be excellent steps forward.

Our response to peak phosphorus requires us to focus on the interconnections between the production, and distribution, of our food, and the disposal of our waste. The biodiversity impacts, resource-use and GHG emissions associated with food production and distribution, are all now within the sights of policy-makers. Reducing the water and energy impacts of the current sanitation system is now too the subject of government policy, as is the pollution resulting from nutrient-rich wastewater entering watercourses. What is required now is a holistic approach that offers solutions to all these problems.

Peak phosphorus is another reason why, in addition to the climate change impacts, the expansion of unhealthy diets, the reality of peak oil and water shortages, calls to vastly increase food production by 2050 through the further intensification of agricultural systems using genetically-modified crops and artificial chemical fertilisers, is not just undesirable, but actually impossible.

As the recent IAASTD report,[130] written by over 400 scientists and supported by over 60 countries, recommended, ensuring food security requires a new food and farming system that is based on the principles of agro-ecology. This can ensure a healthy diet for all and the transformation of waste into a safe resource.

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129 For example, both the EU Directives on UWWT and the Water Framework Directive (WFD) (EU 2000/60) place obligations on the UK government to further reduce the level of phosphorus in UK waterways. The UK Technical Advisory Group has estimated, that in England, approximately 64% of rivers and around 77% of lakes are at risk of failing the proposed WFD phosphate standard for good status. Despite recent investment, the number of sewage works employing chemical precipitation is still in the minority, and it is estimated that a further investment of about £500 million will be required following the latest announcements under the UWWT Directive, potentially adding another 110,000 tonnes of GHG emissions per year.

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RESPONSE FROM A WATER AND SEWERAGE PRACTIONER, THAMES WATER

We welcome this initiative from the Soil Association which will further raise the profile of the issue of limited phosphorus availability, and so generate debate on possible solutions. What is evident is that further research is warranted to understand better the flux of phosphorus in the environment, how much is needed to sustain productive agriculture, and the extent to which phosphorus recovered from domestic sources might contribute to this. Similarly, it would be helpful to understand the practicability, public acceptability and full environmental cost of ecological sanitation – particularly for densely-populated urban areas. Further research might also help address the unanswered question regarding the fate of the greywaters generated in domestic dwellings.

We can take some comfort that in the UK, a large proportion of domestic phosphorus is already recycled to agricultural land as biosolids (treated sewage sludge) and we have long promoted this as being the best environmental option where land availability and transport costs permit. If this material were to regain approval as suitable for organic farming then this would be a very positive step towards securing this valuable recycling route for phosphorus in the medium and longer term, pending the adoption and deployment of ecological sanitation systems.

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