Peak phosphorus – conserving the world's most essential resource

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Abstract:
Phosphorus (P) is one of the three major plant nutrients but it is the scarcest on the planet; at the current rate of exploitation, today's resources will be exhausted in about 70 years; 80% of the extracted P is used as fertiliser. Additional reserves might last another 200 years; when they are exhausted, crop yields will decline rapidly. All living cells require P; it cannot be substituted, unlike fossil fuel. The world's human population was 1bn in 1800, 1.6bn in 1900, today it is 6bn, by 2050 it will be 9bn and is then predicted to stabilise at about that number. For the first time in history more people now live in towns than in the countryside. Food, with its embodied phosphorus flows, from farms to towns. Adults excrete 98% of the P in their diets because they are turning over cells rather than increasing their number. This excreted P and other P ends up in municipal wastewater and is concentrated in biosolids; the amount that escapes in effluent (where it can cause eutrophication) depends on the wastewater treatment. This paper will discuss the dynamics of P, the options for capturing P and the CSR (corporate social responsibility) imperative of not impeding this vital resource conservation.

Keywords: ammonia, biosolids, conservation, CRS, fertiliser, food security, legislation, stewardship, struvite, sustainability, world population

Introduction

Phosphate is essential for all living cells, which would not be an issue if there were abundant supplies, unfortunately, as this paper will review, that is very far from the case. Biosolids and organic resources have a major part to play in the stewardship of this essential resource. As regards threats to the human population, the phosphate crisis is on a par with climate change. Asimov (1974) summarised the importance nicely:

> *"…life can multiply until all the phosphorus is gone, and then there is an inexorable halt which nothing can prevent…. We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation - but for phosphorus there is neither substitute nor replacement.*"

In 1800 the world's population was about 1 billion people. By 1900 it had increased to 1.6 bn; in 1950 it was 2.5 bn; today it is 6 bn and in 2050 it is expected to stabilise at about 9 bn (UN, 2004, Figure 1). For the first time, more people now live in urban areas than in rural areas. Not only has the world's population grown rapidly, those in countries with growing economies (Brazil, Russia, India, China, etc.) want more food and more animal products.

Animal product production is inefficient in energy and in nutrient conservation. The cereals to meat conversion ratios in intensive animal husbandry are 3:1 for poultry, 4.5:1 for pork and 6:1 for red meat (Steén, 1998). All of this means that we need to grow more food, and this food with its embodied nutrients and carbon, is being transferred from rural soils to urban population centres and food processing facilities. At the same time as we shall be demanding more from agriculture, the area of farmable land is expected to decrease because of climate change.

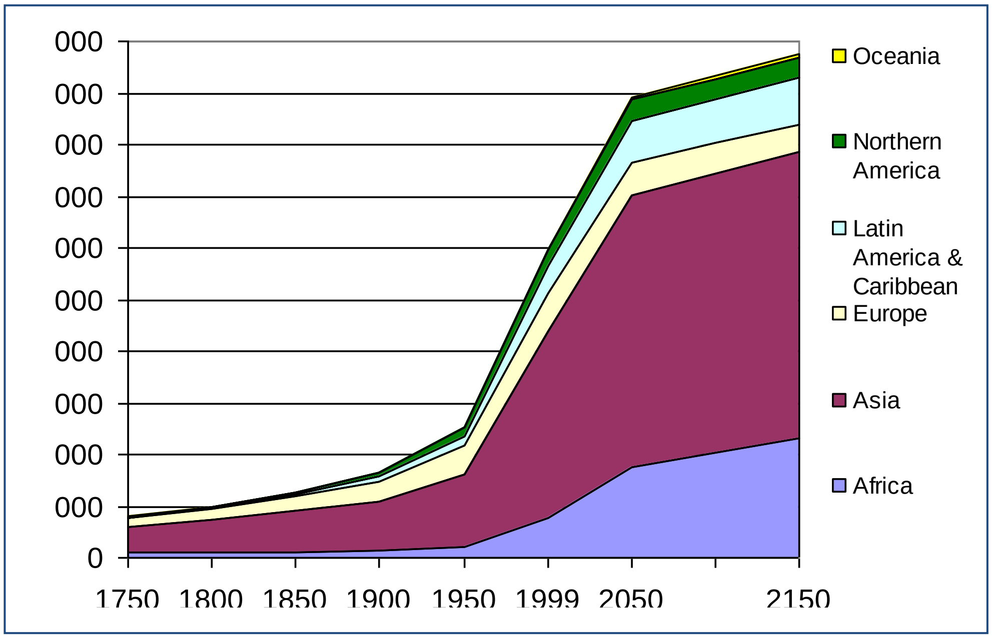

Figure 1 World human population (UN, 2004)

In the 19th century, Europe's agricultural potential was limited by phosphate. Much of the food was imported from the 'newly discovered' continents, especially North America, where it was grown on the fertility accumulated over centuries under natural vegetation. President Franklin D. Roosevelt (1938 quoted by Barnard, 2007) realised the depleted state of the land as a result of having mined the accumulated fertility:

> *"The phosphorus content of our land, following generations of cultivation, has greatly diminished. It needs replenishing. I cannot over-emphasize the importance of phosphorus not only to agriculture and soil conservation, but also the physical health and economic security of the people of the nation. Many of our soil deposits are deficient in phosphorus, thus causing low yield and poor quality of crops and pastures…"*

There are no new worlds from which we can milk fertility. Mineral fertiliser supplies the gap between crop-offtake and the sum of returns (including biosolids, manure and organic resources), fixation and mineralization.

Agricultural science has served humans magnificently. Fertilisers, plant breeding, improved animal genetics, animal and crop protection, weed control and improved husbandry have all raised yield potentials. J.B Lawes patented superphosphate in 1842, guano imports started in 1847, Haber invented the Haber Bosch process for fixing N in 1913; it is all relatively recent in the history of humankind. The unintended consequence of reducing starvation is that we have a population crisis (Figure 1).

Precision farming will target inputs better. Genetic engineering will yield crops that are more resistant to disease, can fix nitrogen, use less (or more brackish) water and perhaps exploit soil phosphorus more efficiently. Even Europe will accept the science of GM for agricultural crops eventually and the cynical vested interests that have been manipulating popular opinion will be seen for what they are. However, whatever other developments are made, we are expecting soils to work ever harder. Organic matter is one of the key factors of soil fertility. It feeds soil biomass, stabilises soil structure (which improves soil water, temperature and aeration and improves erosion resistance) and it is a reserve of nutrients. Soil organic matter breakdown is increased by increased soil temperatures and by cultivation.

To be clear about the fundamentals of crop production it is worth considering the "Law of the Minimum" enunciated by Justus von Liebig, the famous German chemist, in 1872; this is illustrated by Figure 2. If the limit of crop production is like the capacity of a barrel with staves of unequal height, the capacity of the left-had barrel is up to the top of the "nitrogen" stave; this has been lengthened in the right-hand barrel and now potassium is the limiting stave. As Figure 2 shows, the limit could be any of the nutrients or the physical factors that affect plant growth.

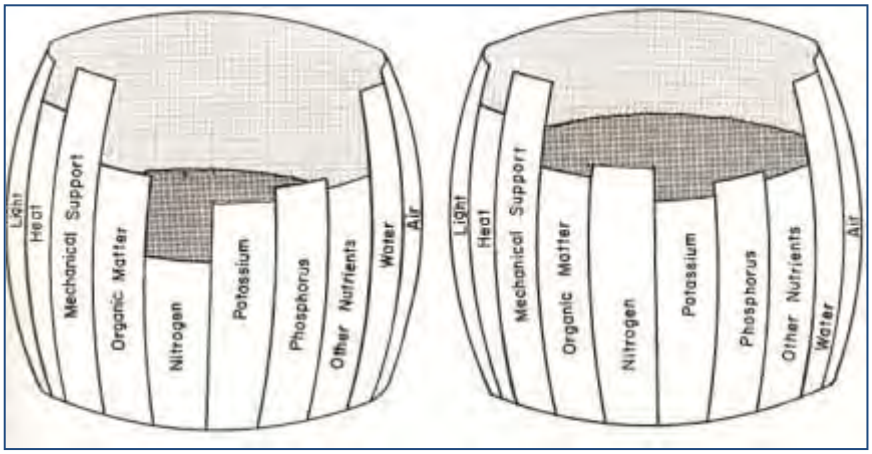

Figure 2 Illustration of the "Law of the Minimum"

One tonne of wheat grain contains approximately 20 kgN, 9.2 kgP_2O_5, 6.7 kgK_2O, etc. A respectable/good wheat yield in the UK is about 10 tonnes/ha. When it is removed from the field, it has to be replaced from somewhere.

Farmers do not squander fertiliser, it is too expensive and they are too aware of the potential for environmental pollution and also for criticism. Great advances have been made in understanding nutrient dynamics in soil and the phasing of crop demands. This information has been disseminated to farmers and the fertiliser industry. The Fertiliser Advisors Certification and Training Scheme (FACTS) administered by BASIS (an independent registration, standards and certification scheme serving pesticide, fertiliser and allied organisations and interests) has also improved practice. The UK water industry gave an undertaking that all who advise farmers about biosolids application rates would be FACTS qualified or subject to training as required by the Assured Crops Scheme.

World supplies

Nitrogen is not scarce: 80% of the atmosphere is nitrogen (dinitrogen gas), so it is not in short supply, it just has to be "fixed" as plant-available forms of nitrogen (urea, ammonia, nitrate, etc.), which requires energy. Rainfall in the UK adds about 50 kgN/ha but drainage of water through soil leaches soluble nitrogen, principally nitrate. Legumes are able to fix nitrogen via a symbiotic relationship with *Rhizobium* bacteria. There is the real possibility of engineering symbiotic N-fixation into wheat and other crop plants eventually.

Phosphorus (P) is the least abundant of the major plant nutrients (Table 1). There is already talk of 'peak phosphorus' (Déry and Anderson, 2007 and Cefic, 2008).

Table 1 Abundance of some elements in the earth's crust (CRC, 2005)

Element	Symbol	% m/m
Oxygen	O	46.50
Silicon	Si	28.20
Aluminium	Al	8.23
Iron	Fe	5.63
Calcium	Ca	4.15
Sodium	Na	2.36
Magnesium	Mg	2.33
Potassium	K	2.09
Hydrogen	H	0.14
Phosphorus	**P**	**0.105**
	Sub-total	99.735%

In 2006 Heffer *et al*. predicted that today's mined resources will be exhausted in 67 years at the current rate of exploitation, i.e. 2073. In addition a total of 208 years' supply of reserves are known, again at the current rates of production (Table 2). Of course to increase food production by between 70% and 100% as has been predicted, we shall require more phosphate.

Table 2 World phosphate rock production and reserves (Mt) (after Heffer et al., 2006)

Country	Production in 2005	Reserves	Reserve base	% of total
Morocco & Western Sahara	28.8	5700	21000	56.7%
USA	35.5	1000	4200	11.0%
South Africa	2.6	1500	2500	8.5%
Jordan	6.4	900	1700	5.5%
China	51.0	500	1200	3.6%
Russia	11.3	150	1000	2.4%
Tunisia	8.2	100	600	1.5%
Brazil	5.5	330	370	1.5%
Israel	2.9	180	180	0.8%
Senegal	1.5	50	160	0.4%
Syria	3.5	60	100	0.3%
Togo	1.0	30	60	0.2%
Other countries	13.1	1000	2500	7.4%
Total	**171.3**	**11500**	**35570**	
Years at 2005 production		67	208	

Déry and Anderson (2007) applied the Hubbert Linearization, which has been used for oil, to the world extraction of rock phosphate from current reserves. The theoretical logistic curve fitted almost perfectly with the real data curve and showed that we passed the phosphate peak for the United States in1988 and for the world in1989.

China has already stopped P exports because it considers P is too important strategically. The largest reserves plus reserve base of P is in Morocco; 56.7% of the world's total. Coincidentally this rock-P has relatively large Cd:P ratio at about 80 mgCd/kgP_2O_5. Today the world is beholden to the Middle East for oil; in the future it will be beholden to Morocco and Western Sahara for P; some consider this inevitability is geopolitically undesirable.

The phosphate cycle

The phosphate cycle in soil is quite complex (Figure 3). P added to soil equilibrates with the different "pools" of availability. The relative sizes of the pools is dependent on the soil type. The pool of "soluble P" from which plants can extract P is very small but it is replenished from the "readily available" pool which is in turn in equilibrium with the "less available" pool and the "very slowly available" pool. It was difficult to explain how sufficient P managed to reach plant roots until it was discovered that roots have associated VAM (Vesicular Arbuscular Michorhizal) fungi that can solubilise P, absorb it and transport it back to the plant's roots, from which they receive food. Sugar beet is perhaps the only crop plant for which VAM has not been found.

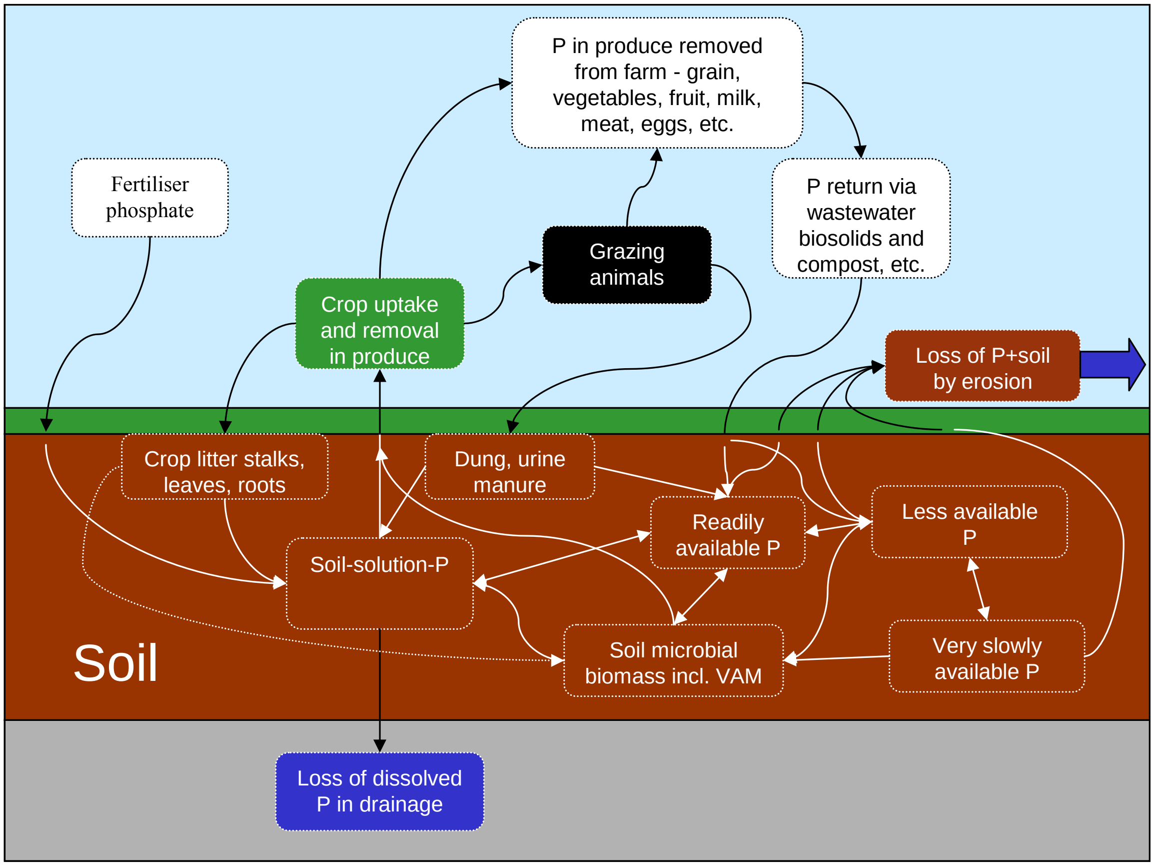

Figure 3 Simplified schematic of the phosphate cycle

Figure 3 shows loss of dissolved P in drainage, this loss pathway generally only lasts a short period of time after soluble P has been added to soil and is largely stopped when the soluble P has equilibrated with the soil's pools of availability. Generally the largest loss pathway is "particulate-P" i.e. loss of soil particles, to which P is sorbed, in runoff surface water erosion.

This equilibration between pools means that changes in crop yield happen more slowly than in the case of nitrogen, which is much quicker to respond. Much of the mineralised nitrogen in soil can be lost through leaching and denitrification between harvest and the start of the next growing season. This does not happen with P. One can under-fertilise and pull down the reserves in the less available pools with only gradual loss of yield but as Roosevelt observed, there inevitably comes a time of reckoning. When the reserves have been drawn down, it takes time and large additions to replenish them.

The British Survey of Fertiliser Use (Defra, 2009) reported that the overall phosphate use on tillage crops in 2008 was 31 kgP_2O_5/ha and on grassland 10 kgP_2O_5/ha; these were the lowest overall rates since the early 1980s. It was a combination of decreased average application rates on both tillage and grassland and a reduction in the proportion of land receiving a phosphate dressing. In 2008, just 52% of all tillage crops and 42% of grassland received a phosphate application, bringing the five-year means down to 58% and 53%, respectively. There are fears that soil reserves are running dangerously low (Johnston, priv. comm. 2008)

Overall phosphate use on tillage crops has gradually declined since 1983, with five-year means of 58 kgP_2O_5/ha in 1983-87, 54 kg/ha in 1988-92, 53 kg/ha in 1993-97, 46 kg/ha in 1998-02, 38 kg/ha in 2003-07 and 36 kg/ha for the period 2004-08. For grassland, the five-year means have been 25 kg/ha in 1983-87, 23 kg/ha in 1988-92, 23 kg/ha in 1993-97, 20 kg/ha in 1998-02, 16 kg/ha in 2003-07 and 15kg/ha for the period 2004-08.

Dietary P – the balance

Like farm animals, humans are inefficient users of dietary phosphate. Adult humans only retain 2% of the P in their food because they are replacing cells rather than laying down new ones. Adult humans excrete about 1.2-1.4 gP/capita.day (about 98% of the P in our diets); to this we can add 1.3-1.8 gP/capita.day from other household and urban sources (Smil, 2000). The combined average appears to be about 2.7 gP/capita.day, i.e.1 kg P/capita.year.

World production of P is about 15 million t P/year, which for 6 billion people is 2.5 kg P/capita.year. 80% of the mined phosphate rock is used as fertiliser; the balance is divided between detergents (12%), animal feeds (5%) and speciality applications (3%), for example, food grade, metal treatment etc.

The P in farm animal manure in the UK additionally equates to about 1.6 kg P/capita.year (from Chambers and Chadwick, 2008). The combined total of urban sources and manure is about 2.6 kgP/capita.year. For 60 million people that equates to 156,000,000 kgP/year which with 11,000,000 ha farmed land would equate to 32 kg P_2O_5/ha.year if we were to capture all of the P from urban sources.

P in urban wastewater

Wastewater treatment can recover 95% of the P from urban wastewater and concentrate it into the sewage sludge that, after appropriate treatment, can be applied to land as nutrient-rich soil improver (biosolids) and/or into side-stream recovered P. Currently we only think about removing P from wastewater to prevent eutrophication when the recovered water is returned to the water environment, but in the future shall we be recovering it as part of the strategy to steward the planet's phosphate? Sweden has a law that targets recycling 60% of the P in urban wastewater by 2015. In 2009 the European Commission launched a contract to investigate "Sustainable use of Phosphorus" (ENV.B.1/ETU/2009/0025). Might there be a European directive with obligations to conserve P? It would give a different meaning to "taking the p***" which used to refer to collecting urine for fixing dyes in the Yorkshire woollen industry, but it seems more important than targeting endocrine active substances, pharmaceuticals, etc. for which there is no evidence of effects on population numbers.

Currently we make P capture/recovery in WwTW more difficult because we return dewatering liquors to the head of the works. These typically represent about 25% of the load of P (and of N) on the WwTW. It is now cost-effective to recover both P and N in sidestream processes and to use the outputs as fertiliser or industrial chemicals rather than trying to capture them into the biosolids (again) or in the case of N, to blow it away (Evans 2006 and Evans and Thompson, 2009). Struvite (magnesium ammonium phosphate) capture has certainly become an entirely viable possibility (Figure 4).

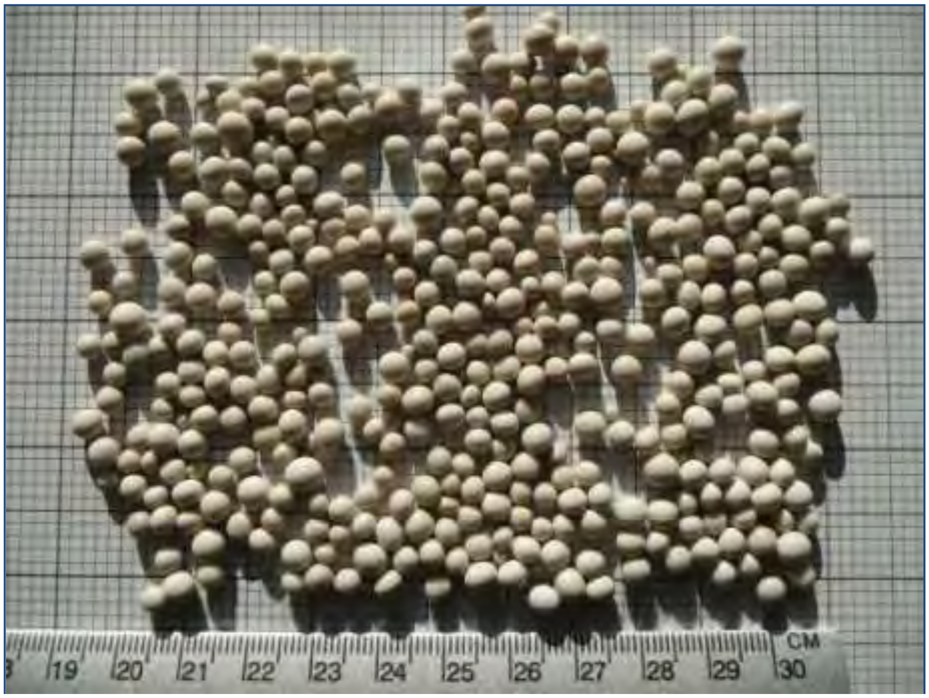

Figure 4 Struvite granules from the Ostara pilot reactor at Severn Trent Water's Derby WwTW, September 2009

Conclusions

More people, requiring more per-capita agricultural production from a declining area of farmable land and a with rapidly dwindling supply of one of the three major plant nutrients, sounds apocalyptic, it is. Climate change has had all the attention but in many ways this phosphate crisis is no less serious. As part of our survival strategy we need to complete the nutrient cycle, capture the P out of urban wastewater and return phosphate in manure, food waste, sewage sludge and other organic residuals to the areas where crops are grown.

It will become evident that as a matter of corporate social responsibility it will be obligatory to facilitate stewardship of P. It seems inevitable that eventually policy makers will wake up to the phosphate crisis and will make legal obligations to capture P, hopefully this will be sooner rather than later. This probability should be factored into biosolids and biowastes treatment strategies so that investment is not stranded by this readily anticipatable policy change. The phosphate industry is already identifying and conserving its historic phosphogypsum waste heaps pending the day when it is financially viable to rework them and extract the residual P. If sludges, biosolids and biowastes have to be burnt, the P should be extracted in advance or the P-rich ash should be preserved pending the day when it is financially viable to recover that P. Regulators should consider this as responsible stewardship of a non-substitutable, irreplaceable and essential resource that is being exhausted at an alarming rate.

Phosphorus is too precious to squander.

Acknowledgements

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