Global phosphorus fluxes and the threat to food security

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Sustainable use of phosphorus

Three key themes now driving P use:

- Meeting food (and biofuel) needs of an increasing population
- Minimizing adverse environmental impacts (meeting environmental legislation/initiatives)
- Protecting finite natural resources

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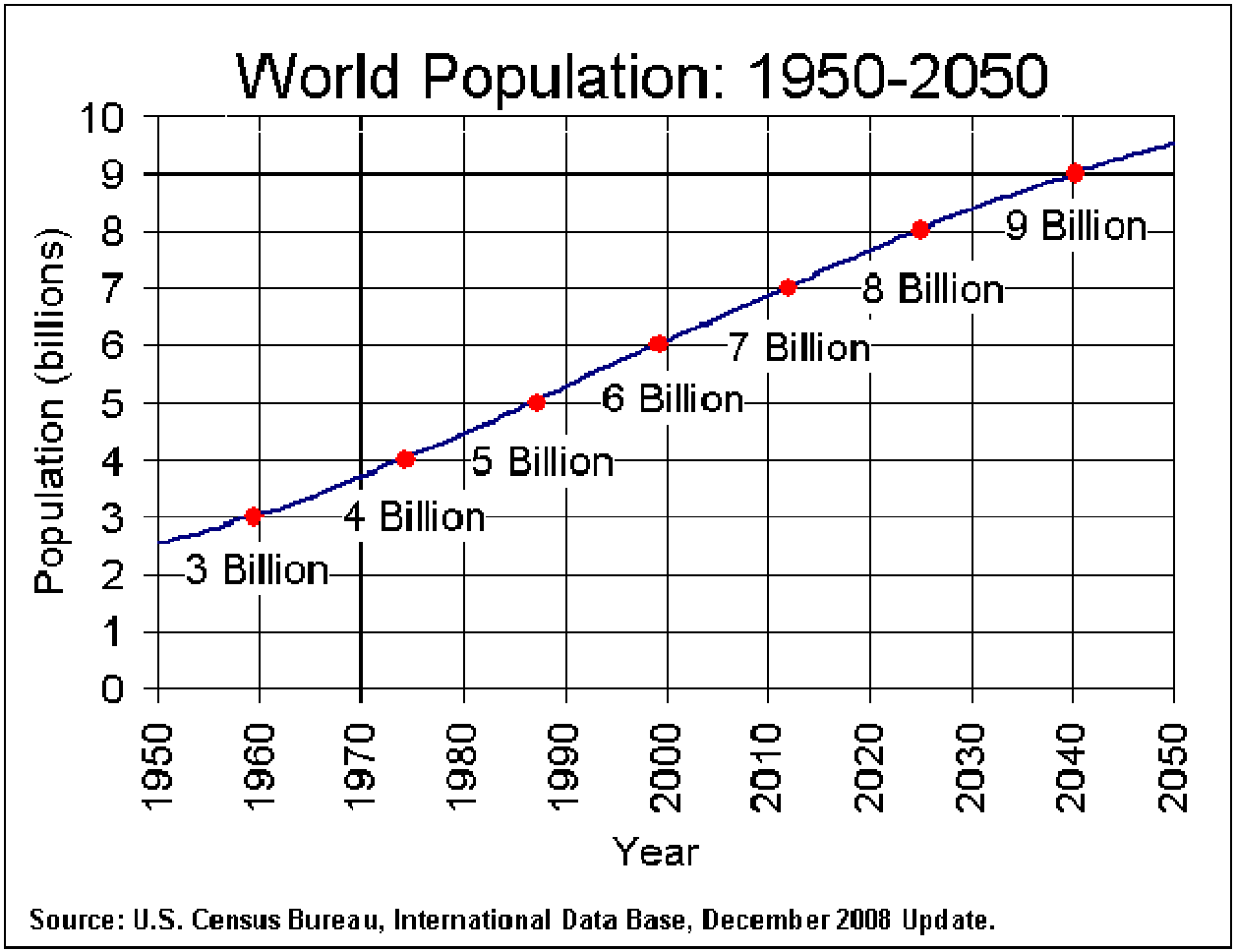
World population growth



Most of the population growth will occur in the developing countries.

Economic growth fastest in Asia

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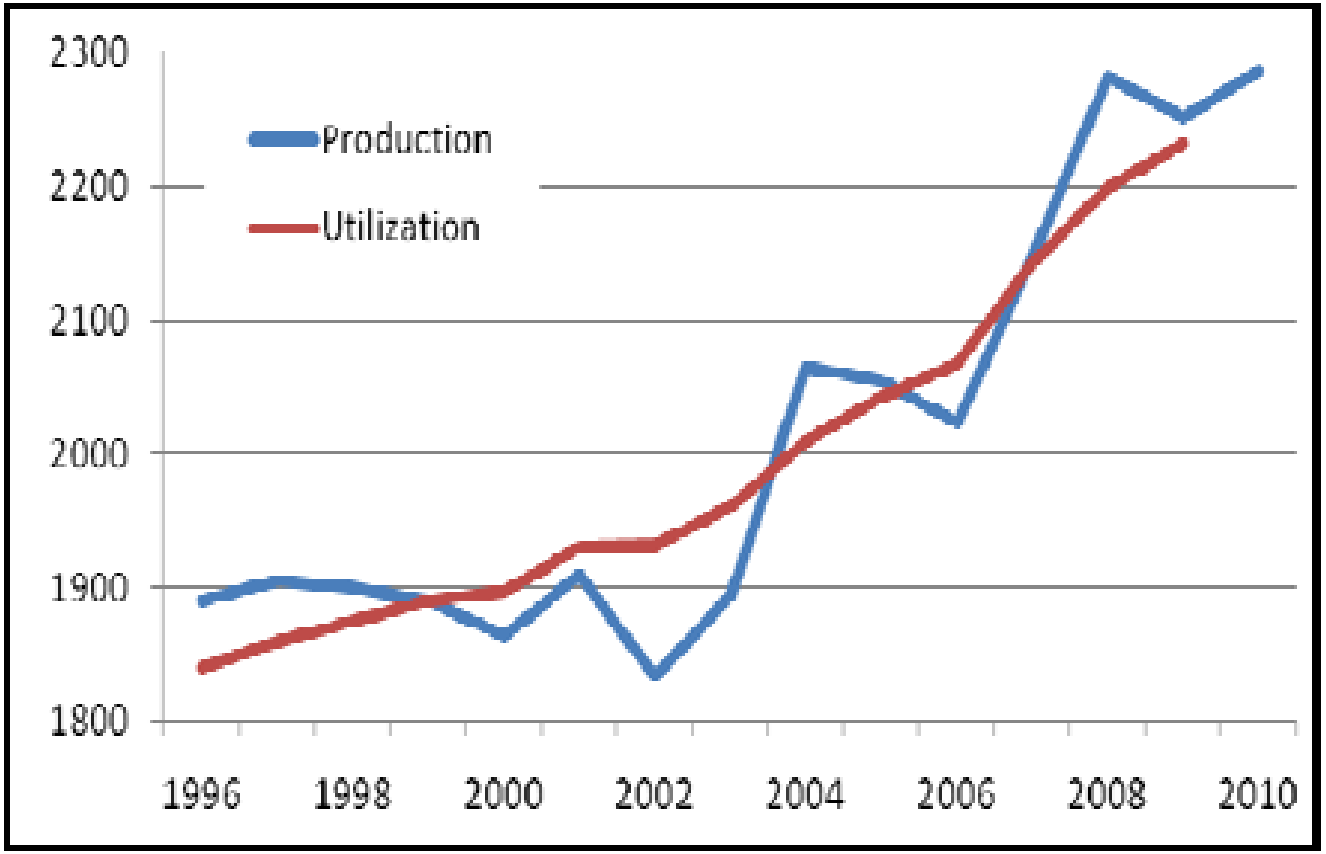
World cereal production/utilization



2010 marked a new record in cereal output

Biofuels market is increasing

Heffer and Prud'Homme, 2010

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Environmental hazards of P use

- Eutrophication of inland and coastal waters

  (£160m/yr in England and Wales)

- Fertilizer manufacture and supply:

  Produces hazardous by-products (radioactive gypsum)

  Produces potentially harmful emissions (F)

  Concentrates harmful metals in the end-products (Cd)

  Uses energy in distribution networks

Global P shortages

NEWS FEATURE

NATURE|Vol 461|8 October 2009

THE DISAPPEARING NUTRIENT

Phosphate-based fertilizers have helped spur agricultural gains in the past century, but the world may soon run out of them. **Natasha Gilbert** investigates the potential phosphate crisis.

Ten years ago, Don Mavinic was working on a way to get rid of a pesky precipitate that plugs up the works of waste-water treatment plants. Known as struvite, the solid crud forms in pipes and pumps when bacteria are used to clean up sewerage sludge.

Mavinic, a civil engineer at the University of British Columbia in Vancouver, Canada, realized that struvite was more than just rubbish. A combination of phosphate, magnesium and ammonium, struvite contains many of the essential nutrients that plants need. Mavinic has developed a way to remove the precipitate during the water-treatment process and he is now selling it as a 'green' fertilizer. His technology was first used commercially in 2007 in a treatment plant in Edmonton, Alberta, Canada. It has since been exported to a plant in Portland, Oregon, which began using it this year. A sewage works in Derby, UK, successfully tested the technology in September.

Aside from finding a use for a troublesome by-product, the recycling of struvite could also help solve a much bigger problem: the dwindling supply of phosphate rock. All life forms require phosphorus in the form of phosphate, which has an essential role in RNA and DNA and in cellular metabolism. Every year, China, the United States, Morocco and other countries mine millions of tonnes of phosphate from the ground (pictured above), the bulk of which is turned into fertilizer for food crops. But such deposits are a finite resource and could disappear within the century.

Experts disagree on how much phosphate is left and how quickly it will be exhausted. But many argue that a shortage is coming and that it will leave the world's future food supply hanging in the balance.

"I am starting to think phosphate rock is becoming a strategic material for many countries. In the future it's going to become more and more valuable," says Steven Van Kauwenbergh of the IFDC, an International Center for Soil Fertility & Agricultural Development based in Muscle Shoals, Alabama. Indeed, as political and social tensions build over the reserves of phosphate rock, the world could move from an oil-based to a phosphate-based economy, say some scientists and industry representatives.

"It is a very curious thing that something so important is so poorly understood and so little talked about in the larger political arena," says Arno Rosemarin, a water-resources specialist at the Stockholm Environment Institute who has researched global phosphate use. Although international leaders have not tended to focus on the potential for phosphate shortages, the issue has been proposed for discussion next month at a United Nations meeting on global food security — an indication that it is starting to attract the attention of the international community.

Just decades left?

In many countries, phosphorus is a limiting plant nutrient in short supply in the soil. So farmers add phosphate-based fertilizers to increase agricultural yields. That has spawned a global phosphate-mining industry with sales totalling in the tens of billions of dollars.

The US Geological Survey (USGS) in Reston, Virginia, estimates that around 62 billion tonnes of phosphate remain in the ground (see graphic). This includes 15 billion tonnes of deposits that are mineable at present and others

V. ARTHUS-BERTRAND/CORBIS

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Europe has called for an urgent review of rock phosphate stocks and how we can manage phosphorus more sustainably.

The Royal Society has now identified phosphorus and food security as a priority topic for research.

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Characteristics of phosphorus supply

- Essential for life (energy, bones)
- Low solubility – key limiting nutrient
- No alternative to natural supplies
- Food production systems reliant on mined P
- Developing countries use too little P
- Developed countries use too much P

The manufacture and use of P is inefficient, environmentally hazardous and wasteful

(ratio of P mined to P consumed is >5)

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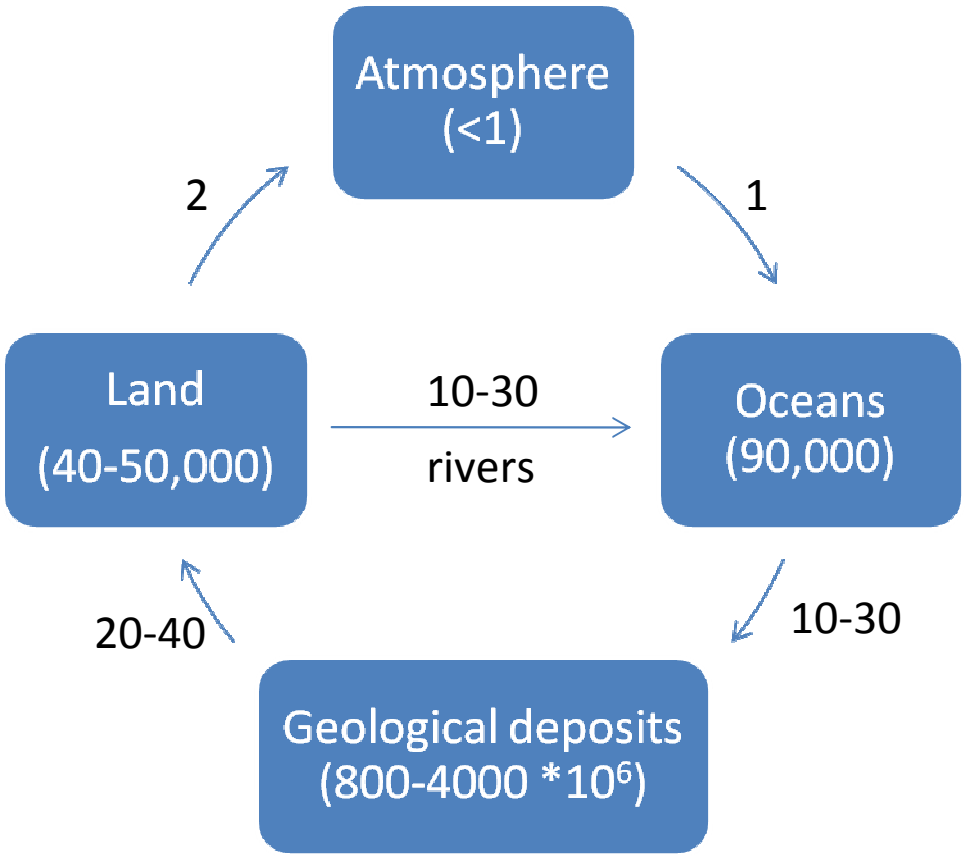
Global P cycle (Tg)



Large stores of P occur in the open sea and in the soil (0-50 cms)

Various sources

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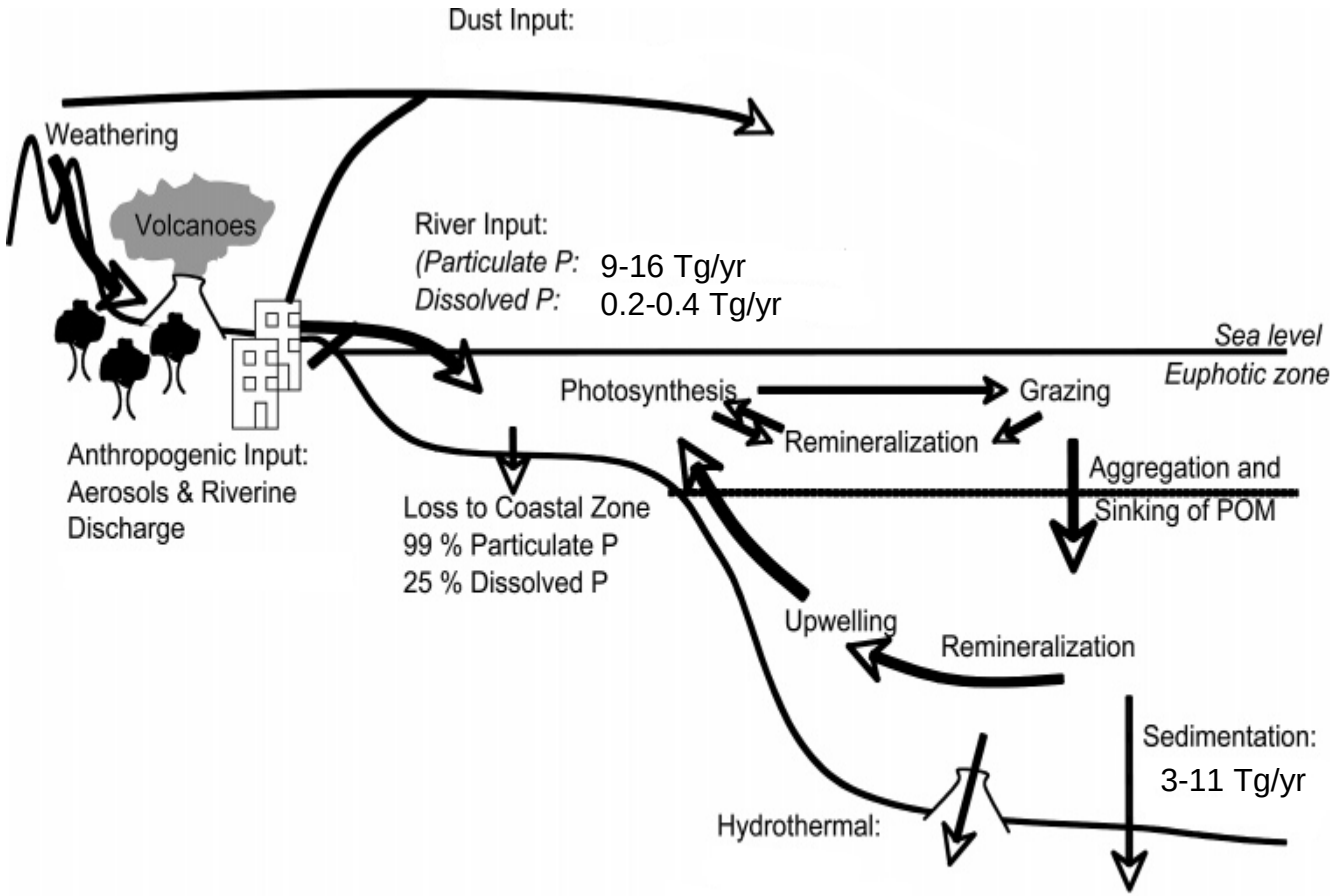
The P cycle in the oceans



Paytan and McLaughlin 2007

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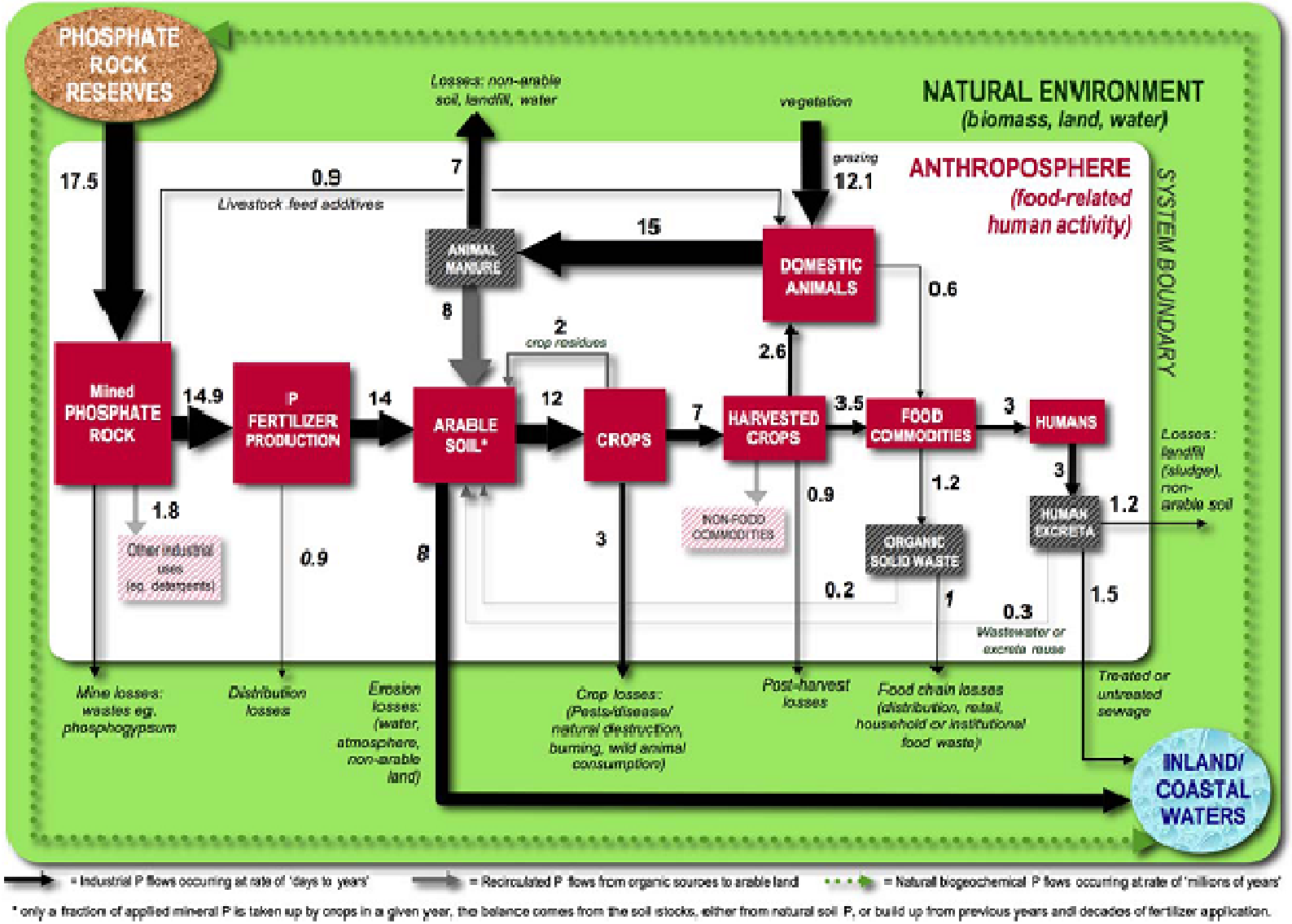
The P cycle on land



Cordell et al. 2009

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Anthropogenic influence

Fluxes (Tg P/yr)	Pre-industrial	Recent (2000)	Future
Crop P	1	12	↑
Manure P	<1	>15	↑
Human P	0.5	3	↑
Organic recycling	<0.5	>6	↑
Inorganic fertilizers	_	15	↑
Riverine P	<10	<20	↑

Riverine export to the oceans has more than doubled.

Smil 2000

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Effects of climate change (e.g. UK)

- Warmer temperatures, wetter winters
- Longer growing season and wider range of crops
- Increased rainfall intensities
- Increased hydrological connectivity during winter

- Increased release of soluble P (soil P, livestock)
- Higher frequency of extreme events - turbidity
- Lower water availability in summer = low flows
- Increased residence time in rivers

Climate change will lead to altered farming patterns and greater eutrophication impacts

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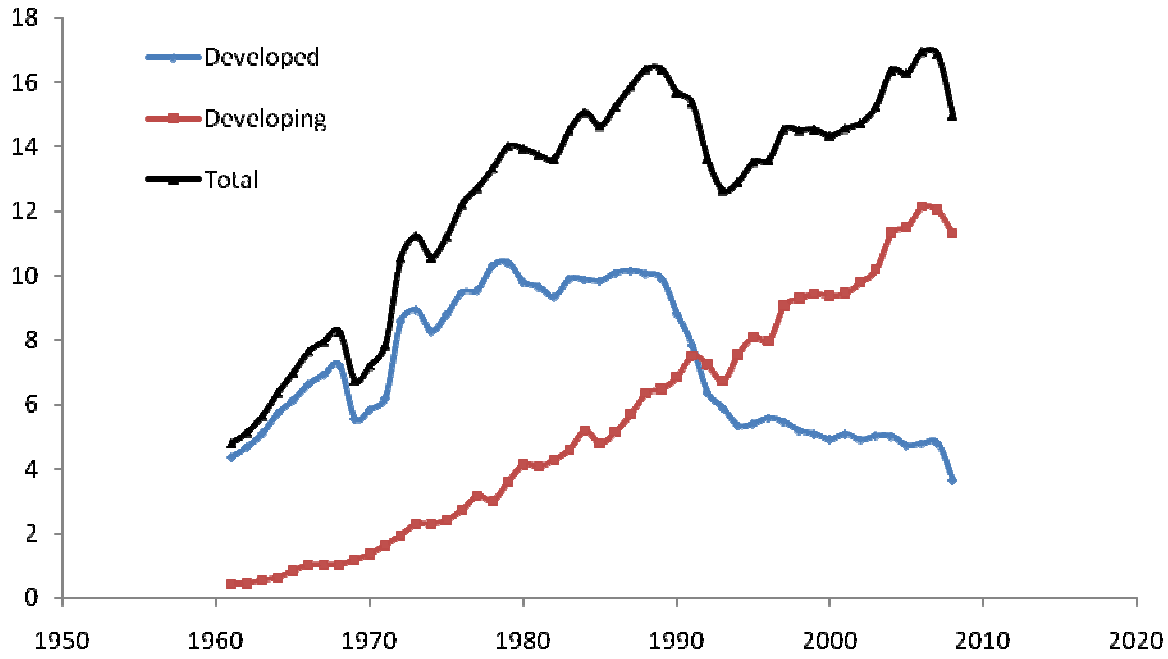
Global fertilizer consumption



Fertilizer consumption now dictated by trends in the developing countries

Developed countries show a marked and consistent decline!

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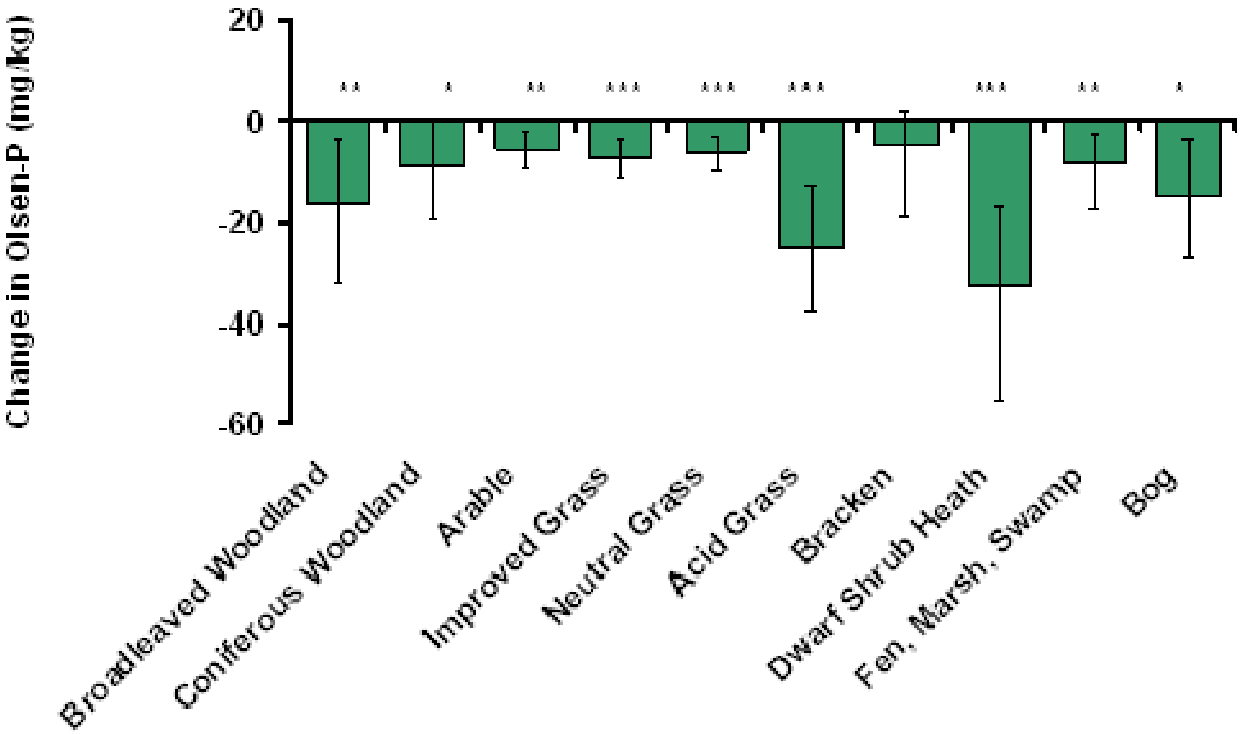
Trends in soil P fertility (UK)



Declines across ALL habitats and not just farmed land.
Decline in fertiliser consumption of over 50% on farmed land.
Is nitrogen deposition stimulating more P offtake in semi-natural habitats?

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Phosphorus as a natural resource

- Rock Phosphate (RP) the major source of P
- A finite reserve (ca. 60 b tonnes) which is dwindling fast
- 80% of RP is used for fertiliser manufacture
- Current RP consumption ca. 160 m tonnes/yr and rising
- Exploitable reserves may last only ca. 100 years
- No alternative sources of P to replace RP
- A threat to global food security
- Volatility in the fertiliser P market/pricing

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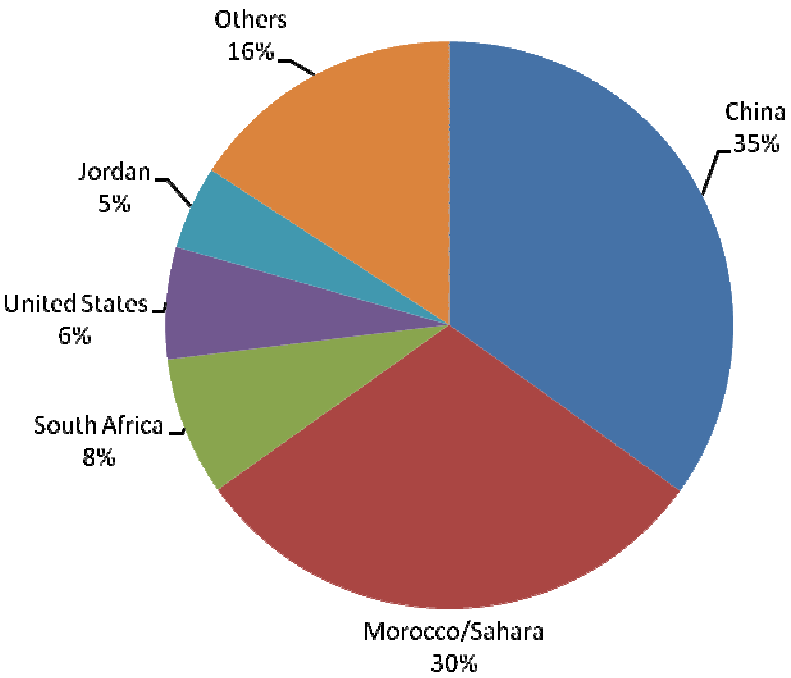
Reserves of rock phosphate



Reserves	2400 Tg
Reserve base	6600 Tg

Most RP reserves are held in a few countries

Issues over future supply routes and cost

Current annual consumption is 18 Tg

Smit et al. 2009

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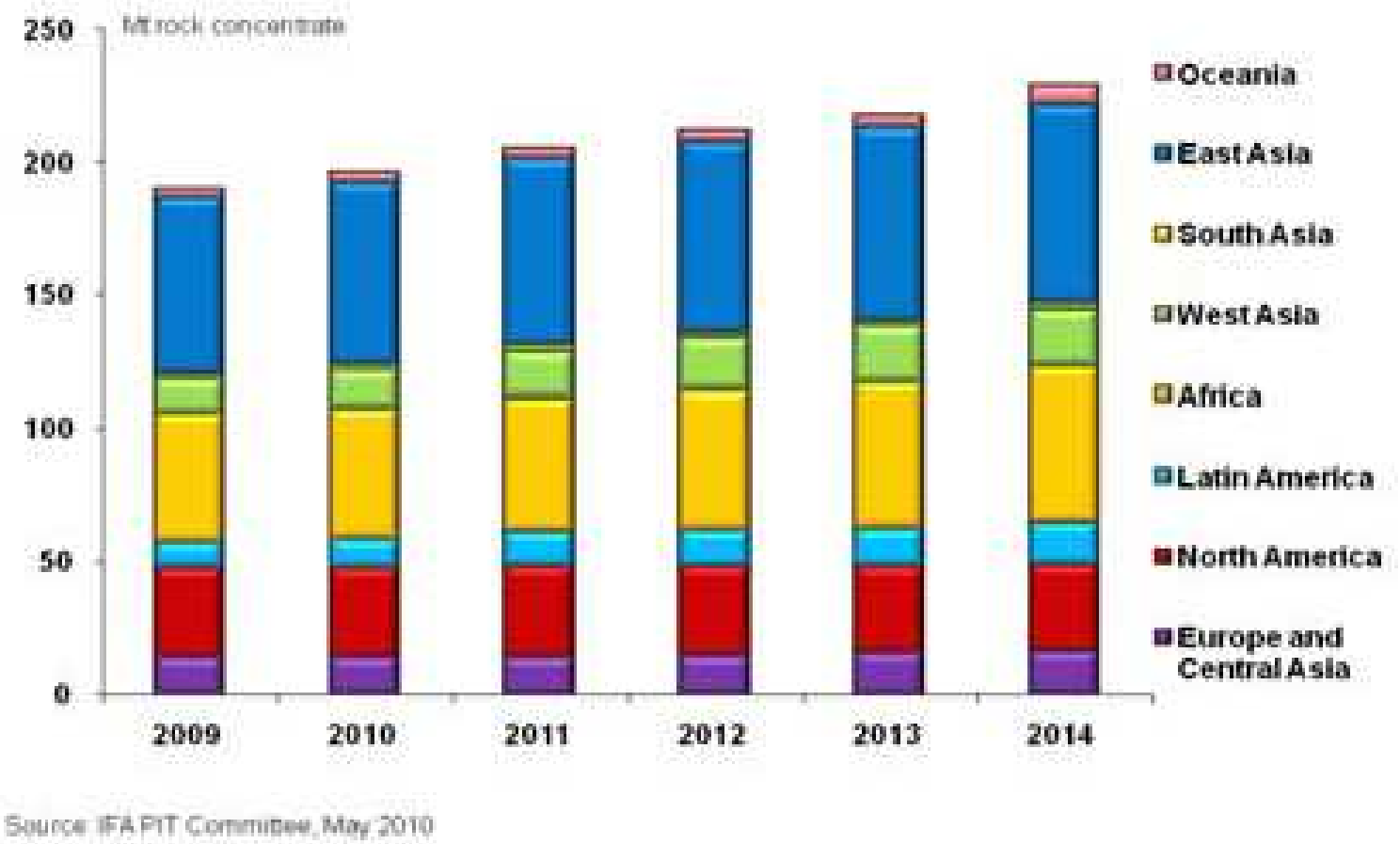
World RP production increasing



Heffer and Prud'Homme, 2010

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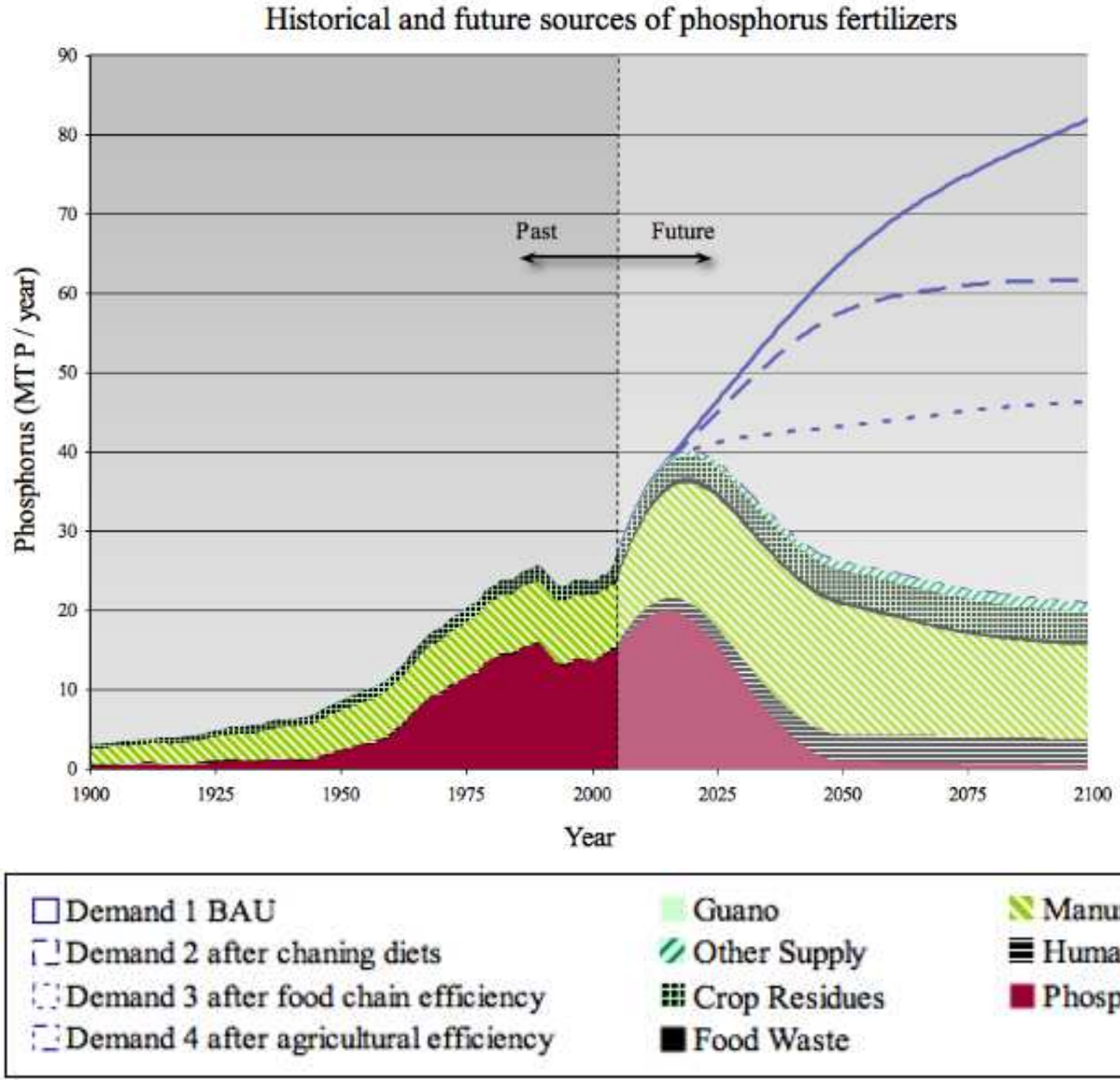
Sustainability of phosphorus use



Cordell et al. 2009

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Key issues for future P sustainability

- Recognising the value of the soil P store
- Improving efficiency of P that we do apply
- Recovering and recycling 'used' P
- Reducing wastage (losses) of P in the cycle

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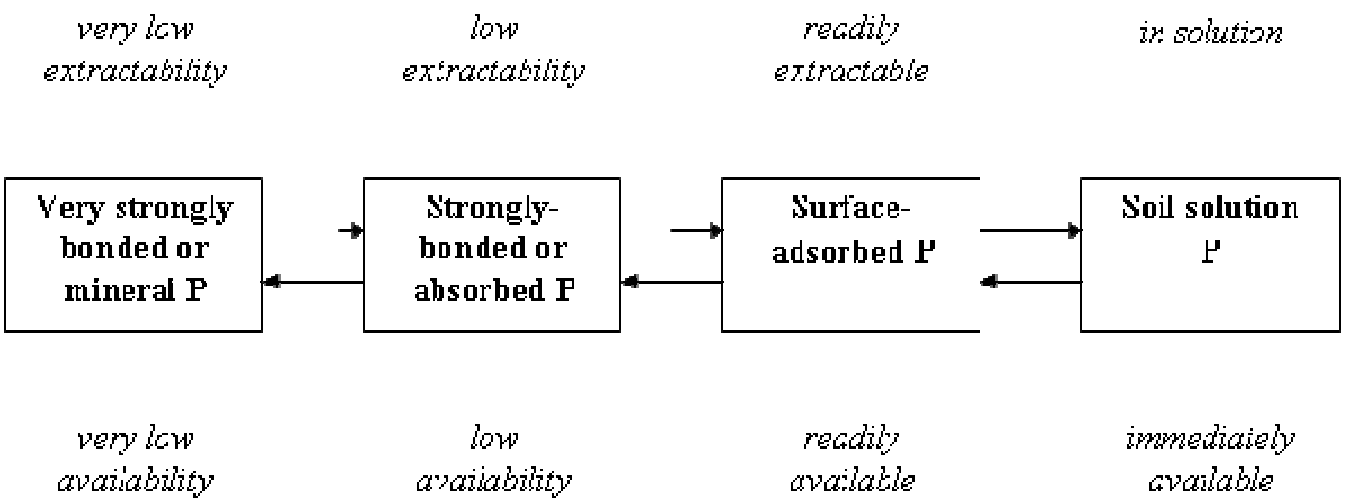
The soil P store



Fixed (residual) P

>70%

Various soil P tests

<30%

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Store of fixed P

- So-called fixed P is not irreversible
- Long-term field trials indicate slow release
- Represents a large store of P:

  Surplus P in UK agriculture since 1930 – 12 Tg

  If we assume ca. 60% of applied P becomes 'fixed'.

  Then store of fixed P is ca. 7 Tg. (Probably more!).

  Store of P worth £4 billion.

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Scientific basis of improving P efficiency

Theoretical approach	Practical alternatives
Reduce fixation of applied P by soil	Buffer pH shift around fertiliser granule
	Neutralise Fe/Al fixation sites
	Use slow-release P (e.g. Struvite)
Improve accessibility to roots	Imbibe seed with soluble/microbial P dressing
	Place P near to seed at drilling
	Apply foliar P during periods of rapid growth
Utilise existing soil P reserves	Identify crop P acquisition traits
	Stimulate soil microbial activity
	Improve rooting systems by plant breeding

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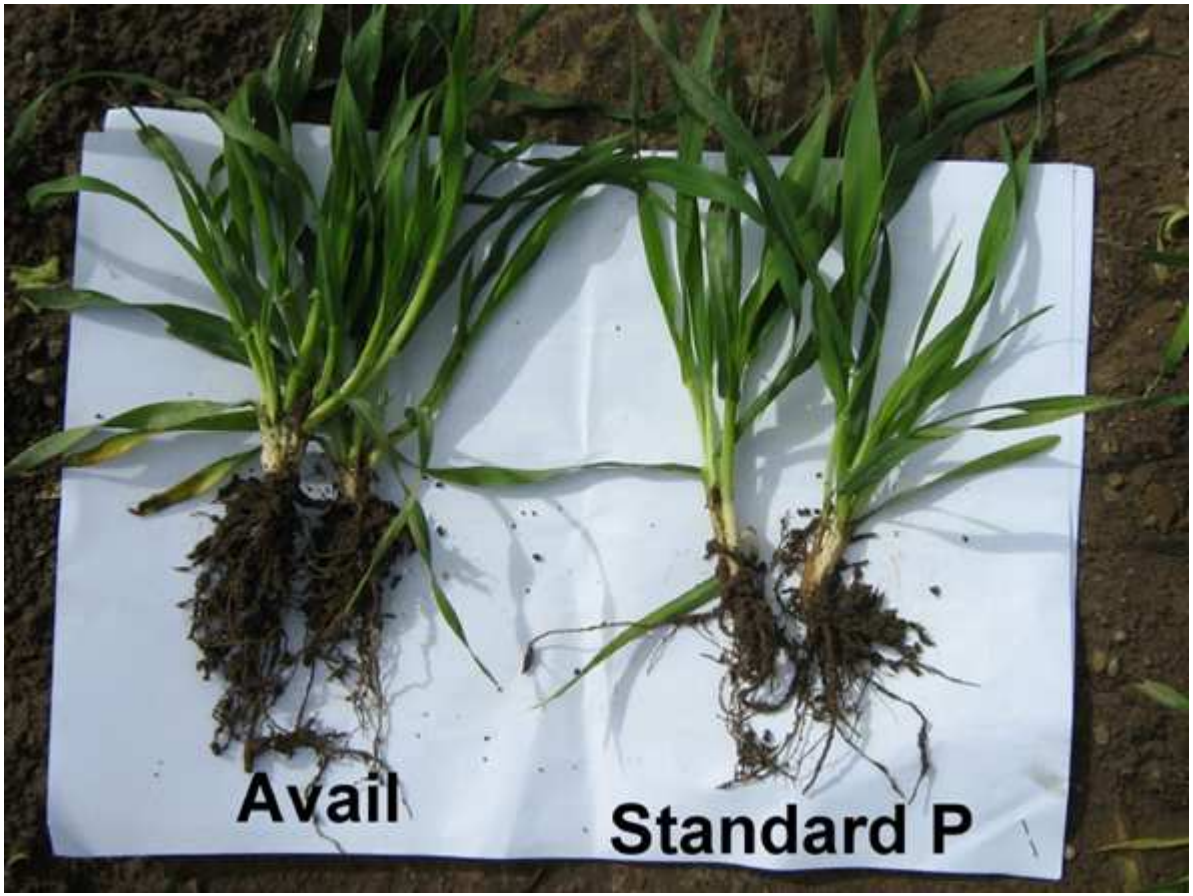
Commercial experience



Crop yield responses of up to 15% on a range of crops including wheat and potatoes

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Some striking rooting patterns

Lolium cultivar

Festulolium cultivar

Festulolium had a much more vigorous rooting pattern and profusion of lateral roots compared to ryegrass!

Crop P contents were greater in Festulolium than in Lolium cultivars

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Recovering wastewater P

NEWS SCAN

Technology

Sewage's Cash Crop

How flushing the toilet can lead to phosphorus for fertilizers BY KATHERINE TWEED

TUCKED AWAY IN OREGON'S WILLAMETTE VALLEY, THREE MASSIVE metal cones could help address the world's dwindling supply of phosphorus, the crucial ingredient of fertilizers that has made modern agriculture possible. The cones make consistently high-quality, slow-release fertilizer pellets from phosphorus recovered at the Durham Advance Wastewater Treatment Facility, less than 10 miles from downtown Portland. By generating about one ton of pellets every day, they are changing the view that such recycling could not be done efficiently. Ostara, the firm that makes the reactors and sells the pellets as Crystal Green, thinks that Durham is one of hundreds of facilities that could use the technology.

Humans excrete some 3.3 million tons of phosphorus annually. In fact, phosphorus from domestic sewage, in addition to fertilizer runoff, has traditionally been a nuisance, because it triggers blooms of algae that deplete local waters of oxygen. In some wastewater plants the element can also bind with ammonia and magnesium to form a mineral called struvite, which keeps phosphorus out of waterways but clogs pipes at the facilities. The growing recognition that cheap supplies of phosphorus will grow scarce in the coming decades has led some nations to consider conservation. Sweden has mandated that 60 percent of phosphate be recycled from wastewater by 2015. In 2008 China slapped a 135 percent export tariff on phosphate.

These pressures have made struvite a hot topic in sewage circles. Japan has been recycling struvite for a decade, but the cost-effectiveness and quality of the pellets varied, according to Don Mavinic, professor of civil engineering at the University of British Columbia (U.B.C.) and co-inventor of Ostara's technology.

WASTEWATER WONDER: Ostara's Crystal Green, a slow-release fertilizer, incorporates phosphorus retrieved from sewage streams.

Durham plant, has been selling Crystal Green since the reactors went online in May. "Having a local source of high-quality slow-release sustainable fertilizer is a great thing," says Jeff Freeman, a regional sales manager at Wilco. "It's something our customers are looking for, and the product has performed outstandingly."

Because of the demand for such fertilizer, the estimated payback of the investment is about five years. Mark Poling, wastewater treatment director at Durham, says it could be faster, because the reactors are functioning better than expected.

The company has sent prototype reactors to wastewater plants in Israel, the U.K. and various cities in the U.S. Shanghai was expected to get a delivery this fall. But Ostara says it is looking to corner the U.S. market first, where the Environmental Protection Agency has been pushing states to more heavily regulate nutrient pollution, including phosphate in sewage effluent.

Wastewater represents a ripe, but small, low-hanging fruit for phosphate recycling, according to experts. It holds only a small fraction of recoverable phosphate, and not all facilities create struvite. "Unfortunately, the phosphorus in human waste is only about 10 percent" of mined phosphate rock, explains David A. Vaccari, director of civil, environmental and ocean engineering

Struvite technology is making significant advances to producing a product which is classed as a fertilizer and not a waste.

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Recovery and recycling of 'used' P

Fertilizer	Soil 1 (pH 5.6, loamy)	Soil 2 (ph 6.8, loamy)	Soil 3 (pH 5.5, sandy)
TSP	100	100	100
Struvite 1	64	104	138
Struvite 2	54	104	68
Incinerated ash	35	57	13
Rock P	6	-13	28

Pot trial with maize receiving 60 kg P/ha, soils had 18-20 mg/kg CAL-P.
Data are % recovery of added P relative to TSP
Field trials showed little difference between struvite and TSP

Perez et al. 2009

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Reducing wastage of used P

- 30-50% losses occur during mining operations
- 1-20% of P losses during application to land
- Majority of P loss to the oceans is via erosion
- Direct discharges from STW to rivers

Conclusions

- Anthropogenic activity has at least doubled the rate of P transfer from the land to the oceans
- Heavy dependence on imports of highly-soluble inorganic fertilizers threaten the long-term supply of P for food production
- Radical rethink in how P is managed from field to global scales required to manage P sustainably
- If we use P more efficiently can we lower background fertility and reduce P imports?

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