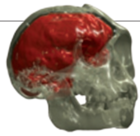
COMMENT

MEASUREMENT The revolutionary origins of the metric system **p.32**



EVOLUTION Hobbit brains were small but packed a punch **p.34**

BOOKS Margaret Atwood muses on why people prefer dystopian fiction **p.35**

FUNDING Britain to require departments to hold female-friendly awards **p.36**

P. DIEDERICH/NYT/REDUX/EYEVINE

Phosphate is mined to produce fertilizers for crops, but phosphorus leaching into water supplies is an environmental hazard.

A broken biogeochemical cycle

Excess phosphorus is polluting our environment while, ironically, mineable resources of this essential nutrient are limited. **James Elser** and **Elena Bennett** argue that recycling programmes are urgently needed.

To meet our demands for energy, humankind has moved masses of carbon from deep underground into the atmosphere, wreaking havoc with the climate. To meet our demand for food, we have moved large amounts of nitrogen from the atmosphere to fields, rivers and forests, devastating ecosystems. To grow our crops we have interfered with Earth's reserves of a third element — phosphorus — which receives much less press and for which we face the unique problem of having both too much and too little.

Since the middle of the twentieth century, humanity has quadrupled the environmental flow of phosphorus[1], an essential element for all forms of life. We dug up geological phosphate reserves to produce fertilizers to feed the Green Revolution, creating a largely one-way flow of phosphorus from rocks to farms to lakes and oceans, and dramatically impairing freshwater and coastal marine ecosystems. Globally, oxygen-depleted marine coastal 'dead zones' caused by nutrient-stimulated algal blooms continue to expand. The Gulf of Mexico's dead zone, averaging more than 17,000 square kilometres in recent years,was forecast to reach record dimensions this year before a tropical storm stirred the waters.

At the same time, concern is growing about how long we can count on cheap supplies of phosphorus for fertilizer: easily mineable deposits of phosphate rock are limited. Unlike nitrogen, phosphorus cannot be pulled from the air and, unlike the carbon in our energy system, there is no known replacement. In 2009, Dana Cordell of the University of Technology in Sydney, Australia, and her colleagues published a 'peak phosphorus' forecast[2] that predicted maximum production around 2030 — an ▶

alarmingly imminent forecast in the light of widespread riots in 2008 sparked by food prices, and a 700% increase in phosphate rock prices from 2007 to 2008.

These issues are not entirely new. In 1938, US President Franklin Roosevelt said it was "high time for the Nation to adopt a national policy for the production and conservation of phosphates for the benefit of this and coming generations". Astonishingly, such a comprehensive policy never emerged, although in the 1970s, the Tennessee Valley Authority set up the National Fertilizer Development Center to study and expand the production and use of phosphate fertilizers. This was the forerunner of the International Fertilizer Development Center (IFDC), headquartered in Muscle Shoals, Alabama.

New research initiatives are emerging to tackle the two faces of phosphorus, including the Sustainable Phosphorus Initiative at Arizona State University in Tempe, of which one of us (J. E.) is a co-founder. The world continues to face deteriorating water quality, uncertainty about future supplies of phosphorus and uncoordinated institutional frameworks. So we need to move quickly beyond academic discussions to creative policy solutions.

POWER IMBALANCE

Estimates of how much readily accessible phosphorus is left have increased since the wave of concern in 2009. But uncertainties surrounding phosphorus supply remain unreasonably large. Last year, economic geologist Steven Van Kauwenbergh at the IFDC produced an assessment of global phosphorus reserves[3], which, by incorporating previously overlooked geological reports from the 1980s, greatly increased the estimated reserves for Morocco and its disputed territory of Western Sahara. This led the US Geological Survey to increase its estimate of accessible global phosphate rock reserves by more than fourfold, from around 15 billion tonnes to around 65 billion tonnes. It is disturbing that these numbers can change by so much so quickly.

More important than the amount of phosphorus in the ground, is how much it will cost to get it out. Overall, three countries control more than 85% of the known global phosphorus reserves, with Morocco clearly in the driver's seat[3] (see 'Global imbalance'). This concentration of power is far greater than for oil, where the dozen members of the Organization of the Petroleum Exporting Countries control 80% of the world's oil reserves. Such a power imbalance is a potential source of tension, given the political turmoil in northern Africa and the fact that developing-world farmers cannot afford phosphate fertilizers even at today's non-monopoly prices. Major regions of the world have diminishing (United States), few (India) or no (northern Europe) phosphorus reserves of their own. Many of the world's food producers are in danger of becoming completely dependent on trade with Morocco, where press reports have emerged of Dubai-style luxury developments being planned in anticipation of phosphorus windfalls.

> ***"More important than the amount of phosphorus in the ground is how much it will cost to get it out."***

The strategic dimensions of phosphorus are beginning to be recognized. In May this year, a workshop sponsored by the US Department of Energy included phosphorus alongside dysprosium, yttrium and other rare earth elements of crucial importance to US national security that face potential supply bottlenecks. Indeed, phosphorus may be included as a 'strategic material' in pending US legislation to assess and secure access to sources of key minerals.

RECYCLE, REDUCE

The solutions to these problems lie in recapturing and recycling phosphorus, moving it from where there is too much to where there is too little, and developing ways to use it more efficiently. Many strategies are simple and readily available, even for poor farmers and developing economies.

Consider the fate of the approximately 17.5 million tonnes of phosphorus mined in 2005, analysed in the paper by Cordell *et al.*[2]. About 14 million tonnes of this were used in fertilizer (much of the rest went into cattle-feed supplements, food preservatives, and the production of detergents and industrial cleaning agents) but only about 3 million tonnes made it to the fork (or chopstick). The largest loss — around 8 million tonnes — was directly from farms through soil leaching and erosion. Much research and effort has already been expended to reduce such losses, including more precise timing and placement of fertilizer along with no-till cultivation, but adoption of these best practices needs to become more widespread. In 2009, the total phosphorus mined had increased to 23 million tonnes, but the general phosphorus pathways and losses have not changed much since the earlier analysis.

On average, about 30–40% of food produced is spoiled or wasted, and this wastes around 1 million tonnes of phosphorus every year[2]. Producing more food within or closer to cities could reduce waste and facilitate recycling by composting and other approaches.

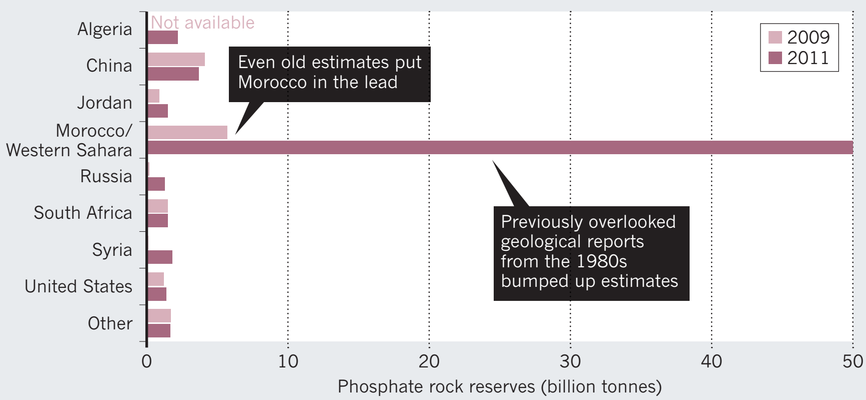
We can also recycle phosphorus from human waste. Each person excretes about 1.2 grams of phosphorus per day[2]; trapping all of this globally would produce about 3 million tonnes per year — about 20% of annual worldwide phosphate fertilizer consumption. Currently, only 10% of phosphorus from human waste is returned to agriculture; one method involves extracting 'struvite' (magnesium ammonium phosphate) at sewage-treatment plants and processing it into fertilizer pellets.

Urine-separating toilets and latrines can help to capture nutrients for return to the soil as well as improve sanitation in the developing world. Already deployed in Europe, the NoMix toilet captures urine in the front and faeces in the back, diverting the urine for recycling at household, neighbourhood or city scale. Urine-separating latrines are now being installed on a relatively large scale in Durban, South Africa, funded by a grant from the Bill & Melinda Gates Foundation. Another low-cost solution is the Peepoo, a single-use, self-sanitizing, biodegradable bag that captures human excreta and can be used, or even sold, as fertilizer 2–4 weeks later. For the poorest of the poor, it would be a potentially radical transformation if their own 'waste' could become a source of income.

According to Cordell *et al.*[2], more than 7 million tonnes of phosphorus were released into the environment annually in the 2000s through animal manure and excreta,

GLOBAL IMBALANCE

Morocco holds the vast majority of global supplies of phosphorus; but these estimates can change disturbingly quickly.



DATA: USGS

causing major water-quality problems. Even if manure were collected, large livestock farms are now often too far away from arable land for transport of the heavy wastes to be economically viable. Combined bioenergy and waste-trapping technologies can help. For example, bioreactors developed by Bion Environmental Technologies in Crestone, Colorado, are being used at a large dairy operation in Pennsylvania to prevent nutrient run-off to Chesapeake Bay; recovered nutrients are slated for return to farms. However, as with manure, transport costs could limit the scalability of this approach. Market incentives might help to make struvite-recovery systems, such as those developed for municipal wastewater-treatment plants, economic for high-density livestock operations.

Reducing the phosphorus requirement for crops and livestock would make it easier for sources of recycled phosphorus to meet agricultural demand. One way to do this is to encourage people to switch to vegetarianism: producing a vegetarian's diet requires 1 kilogram less phosphorus per year than a meat-eater's. This might be a difficult social change to enact, however.

Researchers have recently engineered some plants to increase their ability to scavenge nutrients, including phosphorus, from soils. One approach, published earlier this year, modified *Arabidopsis*, tomato, rice, alfalfa and cotton to overexpress proton-translocating enzymes called pyrophosphatases, which leads to more elaborate root systems and higher production of leaves, fruit and seeds, among other things[4]. So far, these approaches have been limited to the lab and to test plots.

"Dubai-style luxury developments are being planned in anticipation of phosphorus windfalls."

What about livestock? Promisingly, the gene for bacterial phytase, an enzyme that breaks down the phosphorus-rich compounds called phytates, has been introduced into a line of Yorkshire pigs, creating the Enviropig[5]. These pigs produce phytase in their saliva, which allows them to make use of the otherwise undigestible phytates in feed grains. The transgenic pigs produce up to 75% less phosphorus in their manure than do non-transgenic pigs, and do not need phosphate added to their diet. Twelve years after development, the technology is still working its way through federal approval processes in the United States and Canada.

POLICY MEASURES

Together, these measures would help to cut phosphorus-containing waste, enhancing food security while also reducing the polluting effects of phosphorus run-off. But the gaping institutional vacuum for phosphorus governance must also be plugged. Society needs more rigorous, independently verified estimates of pools and fluxes of this critical element as well as reliable ways of estimating the affordability of remaining stocks.

C. WIRSEEN/PEEPOOPLE

The Peepoo biodegradable bag captures human excreta and can be used as fertilizer.

As illustrated by the recent radical adjustment of reserve estimates, we barely know how much phosphorus we have. Current methods to gauge phosphorus reserves rely largely on voluntary provision of proprietary data by private industry and government agencies and, as in the case of Morocco, are often based on relatively old geological assessments. There are other disturbing uncertainties[6]. Estimates of major phosphorus fluxes, such as the loss of phosphorus from agricultural lands, span a three- to fivefold range; others, such as the global return of phosphorus from harvested crops to farms, are essentially unknown.

Attempting to bridge these gaps, new networks of sustainability scientists have come together — as yet loosely organized and lightly funded. Among the first was the Global Phosphorus Research Initiative (now the Global Phosphorus Network), which produced some of the first estimates of potential time frames for phosphorus scarcity[2]. In 2010, the Global Transdisciplinary Processes for Sustainable Phosphorus Management consortium emerged, to connect scientists, industry, business, and government groups at each point of the phosphorus supply and use chain. The Sustainable Phosphorus Initiative sponsored a summit in February 2011 which produced the Phoenix Phosphorus Declaration: a consensus of more than 100 scientists, engineers, architects, designers, farmers, entrepreneurs, artists and communicators on the urgency and opportunities associated with achieving phosphorus sustainability.

Sadly, the message hasn't yet sunk in where it counts. The 2009 United Nations Food and Agriculture Report and the 2010 report of the US National Research Council Committee on Twenty-First Century Systems Agriculture breathe hardly a word about fertilizer supplies, prices and access, instead focusing on the impacts of fertilizer run-off on water quality, and generally emphasizing the effects of excess nitrogen rather than phosphorus. More promisingly, both Sweden and Germany are implementing ambitious directives to recycle up to 60% of wastewater phosphorus, with half of it to be returned to farms and the rest to pastures or forest plantations.

To move further and faster, we call for the establishment of a comprehensive network of national and international science and policy research centres for nutrient sustainability, which should also tackle nitrogen (which has a 'too much' problem[7]) and potassium (which may have similar geopolitical issues of 'too little'). Such centres should pursue research both on fundamental biogeochemical processes in agriculture and on possible policy actions, working closely with practitioners and policy-makers.

One idea is to create phosphorus-emission markets, similar to carbon markets. Some jurisdictions, including 13 US states and some Australian states, are considering these now, primarily to protect water quality. For example, in an arrangement under discussion in Maryland, an advanced wastewater-treatment plant that surpasses federal guidelines for nutrient releases could, through a private broker, sell permissions to release nutrients to other municipalities whose facilities cannot currently meet the targets.

Another, as yet unconsidered, idea might be the creation of national or international strategic phosphorus reserves, similar to the petroleum reserve, to stabilize commodity prices.

As Roosevelt said in 1938: "I cannot overemphasize the importance of Phosphorus not only to agriculture and soil conservation but also to the physical health and economic security of the people of the nation." Nearly 75 years later, it is time to find long-term solutions for one of life's essential elements. ■

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