Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future

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Abstract

Phosphorus security is emerging as one of the twenty-first century's greatest global sustainability challenges. Phosphorus has no substitute in food production, and the use of phosphate fertilizers in the past 50 years has boosted crop yields and helped feed billions of people. However, these advantages have come at a serious cost. Mobilizing phosphate rock into the environment at rates vastly faster than the natural cycle has not only polluted many of the world's freshwater bodies and oceans, but has also created a human dependence on a single nonrenewable resource. The 2008 phosphate price spike attracted unprecedented attention to this global situation. This review provides an updated and integrated synthesis of the biophysical, social, geopolitical, and institutional challenges and opportunities for food security. Remaining phosphorus resources are becoming increasingly scarce, expensive, and inequitably distributed. All farmers require fertilizers, yet a sixth of the world's farmers and their families are too poor to access fertilizer markets. Inefficient use of this fossil resource from mine to field to fork calls for substantial reduction in demand through efficiency and recycling. Phosphorus governance at global, regional, and local scales is required to stimulate and support context-specific sustainable strategies to ensure all the world's farmers have sufficient access to phosphorus to feed the world and ensure ecosystem integrity and farmer livelihoods.

Contents

1. INTRODUCTION: THE SIGNIFICANCE OF PHOSPHORUS FOR HUMANITY

Achieving global food security means ensuring that food is available, accessible, and nutritious to all people at all times (1). However, this is likely to be one of the greatest challenges of the twenty-first century. While food demand is expected to double to feed a projected 9 billion mouths by 2050, many of the essential resources that underpin food production are becoming increasingly scarce (2–4). Food cannot be produced without access to water, energy, land, and nutrients. Yet unlike that of water scarcity, energy scarcity, and nitrogen management, the challenge of phosphorus scarcity is relatively understudied (5). This review critically discusses and synthesizes the latest research and developments around this emerging global challenge.

Phosphorus, like nitrogen and potassium, is a plant nutrient essential to all life that therefore cannot be substituted in food production (6). The importance of phosphorus in crop growth is

PHOSPHORUS: "LIFE'S BOTTLENECK"

The element phosphorus, like carbon, hydrogen, and oxygen, is an essential element and building block for all life, including plants, animals, and bacteria. Phosphorus is a vital component of cell walls, DNA, RNA, and ATP to transport energy to the brain. In plants, phosphorus is essential for cell growth and the formation of fruit and seed development. It therefore has no substitute in food production (6, 145).

Humans acquire phosphorus by consuming plant- and animal-based food. Livestock obtain phosphorus from feed, fodder, grazing, and supplements. Plants in turn obtain phosphorus from soil—their roots draw dissolved phosphorus from soil solution (6). Soil phosphorus is either naturally derived from weathered bedrock or is added through fertilizers, manures, and organic residues. The phosphorus in bedrock has taken millions of years to form, starting as remains of aquatic life on the seafloor that was transferred to the lithosphere over millions of years through mineralization and tectonic uplift (24).

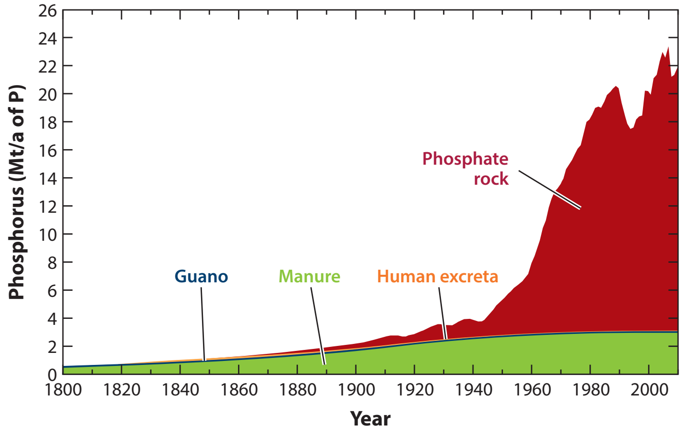


Figure 1

Historical sources of phosphorus for global fertilizer use, including guano, excreta, manure, and phosphate rock (1800–2010). Revised and updated with permission from Cordell et al. (5).

well established: Liebig (7) discovered in 1840 that phosphorus was indeed the limiting nutrient in plant growth. Bones were subsequently collected and ground for their high-phosphate value, and guano (bird and bat droppings deposited over thousands of years), another phosphate source, was soon discovered off the coast of Peru and the South Pacific islands (8). Large phosphate-rich rock deposits were also discovered in the United States that could be easily mined for their fertilizer value (9, 10). Historically, crop production had relied on natural levels of soil phosphorus supplemented with organic sources such as manures, crop residues, and human excreta (11, 12). After World War II, population growth, famine, and urbanization fueled the green revolution to increase crop productivity through new crop varieties and synthetic fertilizers. Phosphate rock mining rapidly increased to keep up with nitrogen production via the Haber-Bosch process (9) (**Figure 1**).

The subsequent use of chemical fertilizers (including phosphorus, nitrogen, and potassium) contributed to feeding billions of people over the second half of the twentieth century by boosting crop yields (13, 14). However, these advantages have come at a serious cost. Humans have altered the global phosphorus cycle by mobilizing four times the natural level of phosphorus from phosphate rock into the environment (15). This has simultaneously contributed to widespread nutrient pollution of many of the world's lakes, rivers, and oceans (16) and to the depletion of a finite resource that had taken tens of millions of years to form. Chemist and science writer Isaac Asimov described phosphorus as "life's bottleneck" and warned 30 years ago, "[W]e 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" (17). However, these concerns were largely ignored as phosphate rock was seen as a cheap and limitless source of phosphorus (11). Today the world's food systems are dependent on inputs from mined phosphate rock to maintain high agricultural productivity (5).

Approximately 90% of phosphate rock is used for food production: 82% for fertilizers, 5% for animal feed, and 2–3% for food additives (18). However, phosphorus resources are inequitably distributed: geographically (with Morocco alone controlling 74% of the world's estimated remaining reserves) (**Figure 7**, see discussion below), among users (mainly farmers), and temporally (between current and future generations) (19).

Humans have disrupted a once closed-looped global phosphorus biogeochemical cycle, with multiple biophysical, economic, social, and technical implications, as summarized in **Figure 2** and

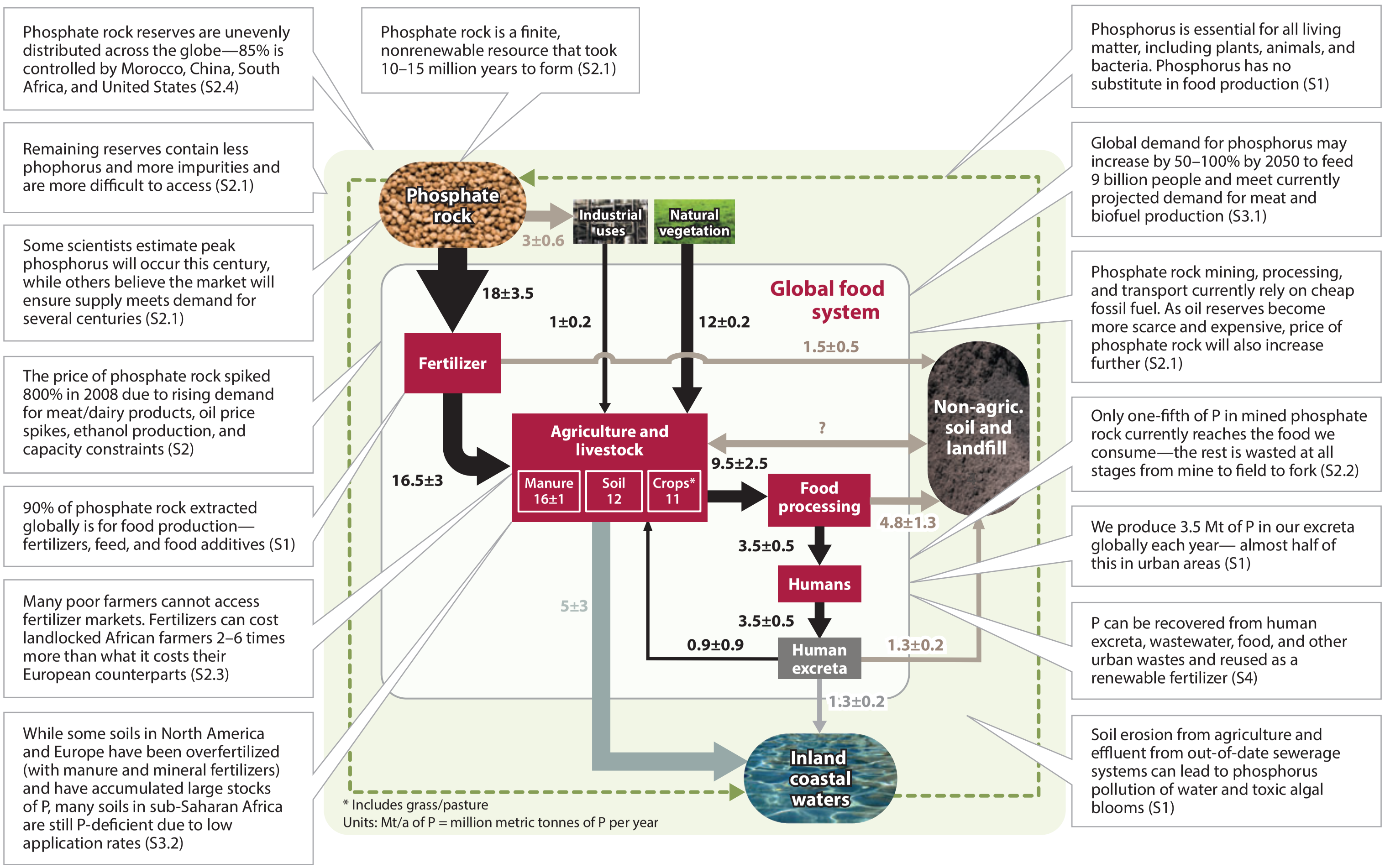


Figure 2

Human intervention in the phosphorus cycle and the global food system, including major phosphorus (P) flows. The figure illustrates the extent and interconnectedness of the global phosphorus challenge beyond physical scarcity of phosphate rock. Corresponding section numbers in this review are indicated (S). Data as indicated in text and **Supplemental Table 1**.

the remainder of this review. Only when these impacts are assessed in relation to one another can the full extent of the global phosphorus challenge be comprehended and hence addressed in an integrated way. **Figure 2** also indicates the major flows of phosphorus through the global food system (see **Supplemental Table 1** for data sources; follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**). Several global phosphorus flow analyses have been undertaken in recent years, with some focusing more on phosphorus fluxes within the food system (5, 20, 21) and others having a greater emphasis on phosphorus fluxes from the food or agricultural system to the world's oceans and fresh water bodies (10, 15, 22, 23).

Supplemental Material

The natural phosphorus biogeochemical cycle is balanced and recirculates phosphorus between the lithosphere and hydrosphere at rates of millions of years. Bedrock gradually weathers to form soil, which is then transported to rivers and oceans via wind/water erosion, which eventually sinks to the seabed together with remains of aquatic life and forms sedimentary rock, ultimately surfacing due to tectonic uplift (24).

Today, on a human timescale, phosphorus predominantly flows in a one-way direction through the global food system from mines to the oceans via agriculture at rates over three times natural flow (15, 22). Each year, approximately 21 ± 4 megatonnes per year of phosphorus (Mt/a of P) in phosphate rock is mined and cleaned, of which 18 ± 3.5 Mt/a of P is then reacted with sulfuric acid to produce phosphoric acid, a more concentrated and plant-available form of phosphate for fertilizers (5, 18, 23, 25). Some 15–30% of phosphorus is lost during mining and processing, 3 ± 0.6 Mt/a of P is used for industrial purposes, and a further 1.5 ± 0.5 Mt/a of P ends up stockpiled onsite in the fertilizer by-product phosphogypsum or lost due to spillages (18, 26, 27).

Phosphate fertilizer products, including di-ammonium phosphate, mono-ammonium phosphate, nitrogen-phosphorus-potassium (NPK), triple super phosphate, and single super phosphate (amounting to some 16.5 ± 3 Mt/a of P), are traded globally and applied to the world's agricultural fields and grasslands (23, 28, 29). Plant roots take up only 15–30% of the phosphorus applied annually in fertilizers (in addition to residual soil phosphorus) that is subsequently dissolved in soil solution (30). Approximately 11 Mt of P is taken up by crops and grassland each year, while 12 Mt of P is estimated to be added to the soil stock each year. Some 5 ± 3 Mt/a of P in soil is exported via wind and water erosion from fields to water bodies and nonagricultural soils. Phosphorus enters into the livestock sector in the form of feed, fodder, supplements, fertilized pastures, or natural grasslands. Phosphorus leaves the world's feedlots, pastures, and grasslands in animal products, and the remainder ends up in manures and eroded soils. Manure alone is estimated to contain some 16 ± 1 Mt/a of P from the world's 63 billion head of livestock (11). Half of this is productively reused in agricultural or grassland soils, while the other half is estimated to be lost to nonagricultural soils or water.

Some 9.5 ± 2.5 Mt/a of P in crops and animal products (such as meat, milk, eggs, and fish) are then processed into food products, of which 3.5 ± 0.5 Mt/a of P is physically consumed by the human population, with the remaining 4.8 ± 1.3 Mt/a of P either processed as nonfood products (e.g., nonfood oils), wasted (e.g., spoiled food), or lost as inedible components (e.g., banana peels and egg shells) and predominantly destined for landfills or compost heaps. Of the phosphorus in food consumed by humans, almost all (98%) leaves the body in urine and feces (31). A fraction of this (0.9 ± 0.9 Mt/a of P) is reused in agriculture via application of treated or untreated wastewater and biosolids. The ultimate fate of this phosphorus therefore is to enter freshwater or oceans (6.3 ± 3.2 Mt/a of P) or, to a lesser extent, nonagricultural soils and landfills.

Bennett et al. (22) estimate that the human intervention in the global phosphorus cycle has mobilized an additional 22 Mt/a of P to enter the ocean, beyond natural cycling. Excess nutrients in freshwater and oceans leads to eutrophication, which can lead to excessive growth of toxic algal blooms, with adverse consequences for aquatic ecosystems, water quality, and recreation (15). In

2008, the World Resources Institute (32) reported more than 400 dead zones around the world as a result of eutrophication, from the Baltic Sea, to the US's Chesapeake Bay, to Australia's Great Barrier Reef (33, 34). In the United States alone, eutrophication is estimated to cost US$2.2 billion annually (35). Concentrated phosphorus in urban wastewater effluent discharged to lakes and rivers coupled with diffuse nutrient pollution leaking from agricultural fields are the main pathways leading to eutrophication (36). The most effective ways to manage eutrophication are therefore to remove phosphorus from wastewaters discharged into water (37) and to improve land-based practices to reduce soil erosion to water (38).

Although the influential "planetary boundaries" assessment (39) suggested that current global phosphorus use is within a "safe operating space," Carpenter & Bennett (40) revised this analysis, noting that the safe threshold has already been crossed when freshwater (in addition to oceanic) eutrophication is also included in the assessment. Furthermore, the planetary boundaries framework does not include depletion of phosphate reserves or phosphate stocks relative to use (41).

2. DIMENSIONS OF PHOSPHORUS SCARCITY

Over the past few decades, awareness of and research on phosphorus as a pollutant contributing to eutrophication and the world's dead zones has increased and reached the global agenda, such as when phosphorus flux was identified as one of the world's nine planetary boundaries (39). Concerns around phosphorus scarcity were limited to discussions within specific groups (e.g., 42) and the occasional forewarning by scientific and social commentators (11). A future scarcity of phosphorus and the implications for food security were largely ignored in the dominant discourses on global food security (e.g., 14, 43, 44), global environmental change (e.g., 39, 45), and resource scarcity (41, 46).

However, this discourse underwent abrupt changes in 2008 when the price of phosphate rock spiked 800% from US$50/tonne to US$430/tonne (**Figure 3**). This occurred against a backdrop of food and other commodity price spikes and shortages the same year. Food and fertilizer riots ensued among the poor from Haiti to India as consumers and farmers could not access sufficient resources (41, 47). However, this short-term crisis triggered substantial and sudden interest in the longer-term issue of global phosphorus scarcity. A flurry of science media reports (e.g., 48), scientific articles (e.g., 5, 49), and new multistakeholder platforms (e.g., the Global Phosphorus Research Initiative, the Dutch Nutrient Platform, the US Sustainable Phosphorus Initiative, and Global TraPs) emerged directly addressing the issue and raising awareness at the international level (50, 51). Having been ignored in the past, the scarcity of phosphorus began to appear in authoritative reports by key international documents on global food security (23, 52, 53). Nevertheless, many of these discussions have been limited to physical scarcity of phosphate rock (e.g., timeline for depletion and longevity of reserves) rather than addressing the wider, complex issues associated with scarcity.

PHOSPHORUS SCARCITY: NOT JUST PHYSICAL

Although often perceived narrowly as the size and longevity of geological phosphate reserves, phosphorus scarcity has at least five dimensions beyond physical scarcity: economic, managerial, geopolitical, and institutional scarcity all contribute to hindering the accessibility and availability of phosphorus for food security (41). Often resource scarcity is more about ineffective management and governance than simply physical scarcity (101).

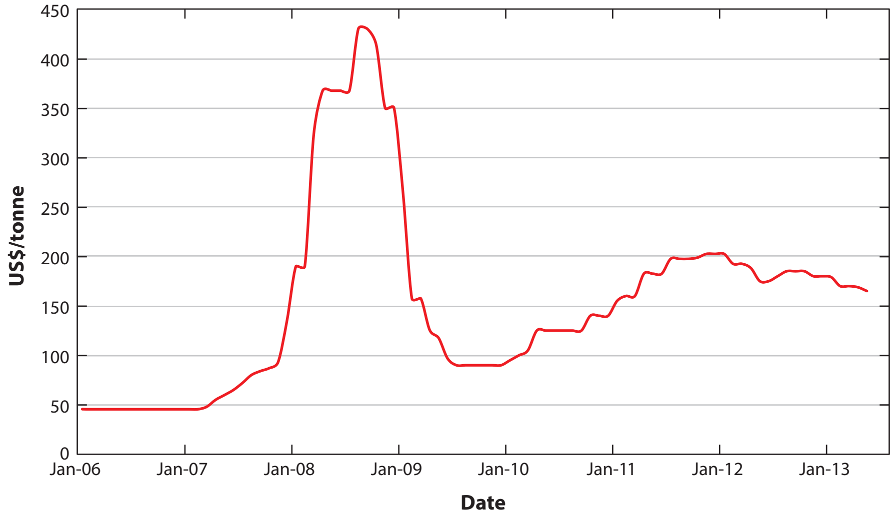


Figure 3

Phosphate rock commodity price 2006–2013, indicating 2008 price spike at US$431/tonne. Data sources: World Bank Commodity Price Data (53a); Minemakers Limited (53b). **http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTDECPROSPECTS/0,,contentMDK:21574907~menuPK:7859231~pagePK:64165401~piPK:64165026~theSitePK:476883,00.html.**

2.1. Physical Scarcity

Phosphate rock is a finite resource that has taken tens of millions of years to form from the mineralization of shells and dead aquatic life followed by tectonic uplift (24). Like other nonrenewable resources, the cheaper and easier-to-reach deposits are typically mined first (54, 55). Scientists and industry agree that although the element phosphorus will never run out per se, high-grade reserves will one day be depleted, meaning that remaining phosphate rock reserves will have a lower phosphorus concentration, will contain more impurities (such as clay), will become physically harder to access, will lead to more waste being generated per tonne of phosphorus extracted, and will subsequently result in increased input and extraction costs (18, 55–61, 62). For this reason, scientists and industry caution that this precious resource upon which life depends should be used efficiently (5, 52, 55, 63).

Where the debate and scientific uncertainty lie is in the size and longevity of remaining phosphate rock reserves. **Figure 4** compares six recent studies on the longevity of global phosphate reserves (5, 55, 63–68) (the different assumptions for each study are outlined in **Table 1**). The underlying reasons for such a vast range of estimates include assumptions about demand, supply, and the depletion model employed.

First, regarding future demand, some estimates, such as Van Kauwenbergh (55) and Fixen (63), assume phosphate demand is fixed. They make these estimates despite future projected demand increases associated with population growth, dietary changes, and nonfood demands such as biofuels (21, 23, 69).

Second, estimates differ due to assumptions regarding future supply of global phosphate rock. Estimates for phosphate rock reserves and resources are dynamic figures (55, 70) because they are based on what is considered technically and economically feasible at a given point in time, in addition to any new reported discoveries. Reported reserve estimates collated by the US Geological

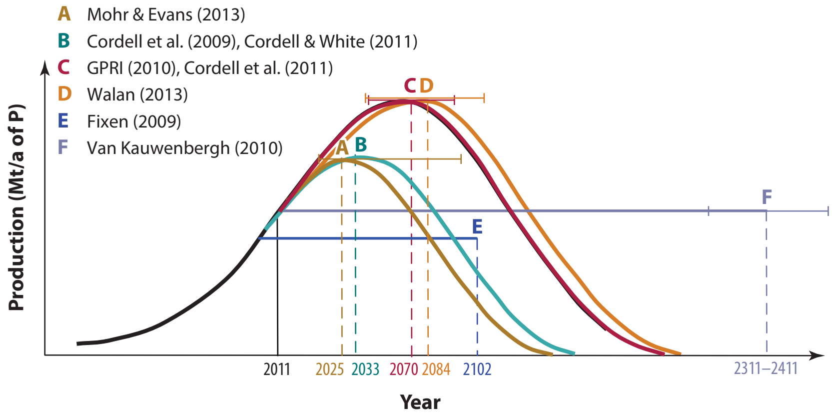


Figure 4

Global phosphate depletion scenarios by different authors, indicating different depletion or peak years based on different assumptions outlined in **Table 1**. [Studies depicted are A. Mohr & Evans (64); B. Cordell et al. and Cordell & White (5, 65); C. GPRI (144), Cordell et al. (66); D. Walan (68); E. Fixen (63); F. Van Kauwenbergh (55).]

Table 1 No consensus: recent studies on global phosphate depletion and underlying assumptions (see the authors' scenarios depicted graphically in Figure 4)

Author	Global phosphate depletion scenario(s) and assumptions
A. Mohr & Evans (64)	Peak phosphorus scenarios based on a dynamic, bottom-up demand-production interaction model aggregating regions, not a Hubbert model; using USGS 2012 phosphate reserve data for URR; peak phosphorus scenarios: 2025 (low), 2030 (most likely), 2120 (high)
B. Cordell et al. and Cordell & White (5, 65)	Simplistic peak phosphorus modeling based on Hubbert curve and least-squares optimization fixing USGS 2008 phosphate reserve data as URR
C. GPRI (144), Cordell et al. (66)	Simplistic peak phosphorus modeling based on Van Kauwenberg (55) phosphate reserve data as URR, using Bayesian statistical analysis; peak phosphorus scenarios: 2051 (low), 2070 (most likely), 2092 (high).
D. Walan (68)	Peak phosphorus scenarios based on logistic and Gompertz curves aggregating top country production; peak phosphorus scenarios: 2030 (low), 2084 (most likely), 2131 (high)
E. Fixen (63)	R/P fixed ratio model, assuming no-growth production rate (fixed at 2007/2008), and phosphate reserves based on USGS 2009 estimates
F. Van Kauwenbergh (55)	R/P fixed ratio model, assuming no-growth production rate (fixed at 2009) based on author's revised phosphate reserve estimates for Morocco
Van Vurren et al. (67)	Depletion scenarios based on systems dynamic modeling of four Millennium Ecosystem Assessment scenarios for phosphorus consumption in 2050; best-case scenario: 20–35% depletion by 2100; worst-case, 40–60% depletion by 2100

Abbreviations: IFDC, International Fertilizer Development Center; R/P, reserves/production; URR, ultimately recoverable resources; USGS, US Geological Survey.

Survey (USGS) (see **Figure 7** and the related discussion below) vary year to year (most notably a quadrupling of estimates of Morocco's share between 2009 and 2010), thus affecting the results of authors' depletion studies. For example, the Cordell et al. (5) peak phosphorus study relied on 2009 USGS reserve data (best available at the time of publishing), resulting in a peak year of 2033 (B in **Figure 4**). When the same model is updated with the 2010 reserve data range from the International Fertilizer Development Center (IFDC) (see Reference 55), the peak curve shifts several decades to 2051–2092 (C in **Figure 4**; see References 66, 144). IFDC estimates (see Reference 55) reestimated global phosphate rock reserves at 60,000 Mt, up from 16,000 Mt the previous year (58). This quadrupling of estimated reserves was largely due to revising Morocco's share from 5,600 to 51,000 Mt of phosphate rock. However, these revisions were based on literature from 1989 and 1998, not on new geological studies. The revised data have been largely adopted by industry and scientists alike (including USGS), due to a lack of other reliable public data. As cautioned by Edixhoven et al. (71), the IFDC's revised global reserve estimates are largely inconclusive and hypothetical, and the IFDC definitions contravene the global development toward more common criteria in resource reporting, leading to "pervasive confusion" and a high degree of error (71, p. 1005).

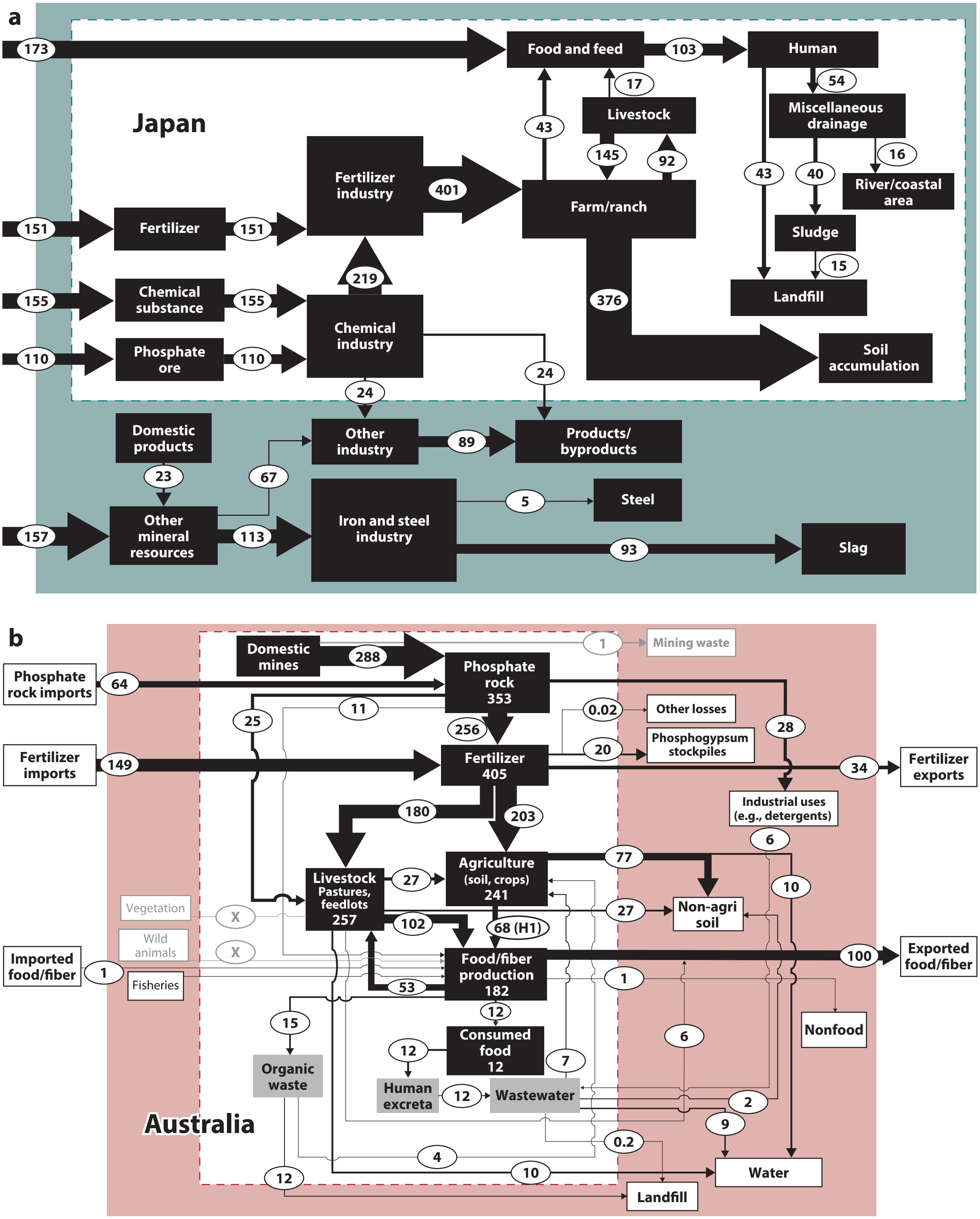
Third, estimates vary depending on the type of depletion model used and the assumptions they entail. The reserves/production (R/P) fixed ratio model employed by Van Kauwenbergh of IFDC (55) and Fixen (63) optimistically assumes that all the reserve can and will be used, and thus estimates based on this model lead to a later depletion date (72) [300–400 years as suggested by IFDC (55)]. Bell-shaped curve models, such as the peak phosphorus model, assume—less optimistically and based on empirical evidence with phosphate and other nonrenewable resources—that the critical point in time occurs not when 100% of the reserve is depleted but rather far sooner owing to economic and energy constraints (65, 72, 73). Reserve figures give an indication of "tonnes of phosphate rock," without indicating the quality (e.g.,%P_2O_5) and ease of extraction. Recent peak phosphorus studies by Mohr & Evans (64) and Walan (68) using country-level USGS reserve data for ultimately recoverable resources (URR) indicate a likely production peak this century. Other studies skeptical of peak phosphorus modeling suggest that Hubbert-style curve fitting is not robust in the situation when URR is not already known (74) or that such bell-curve modeling does not adequately deal with dynamic factors such as changes in cost, demand, and technological advances and that perhaps Hubbert-style modeling better serves as "early warning indicators" (70).

2.2. Managerial Scarcity

Phosphorus is also scarce because of mismanagement of the resource. That is, inefficient use of phosphorus hinders its availability and accessibility in food production. Ultimately, only one-fifth of the phosphorus mined globally for food production finds its way into the food consumed by the global population (**Figure 2** and Reference 5). This is due to inefficiencies and losses at all stages of the food system: mining, fertilizer production, fertilizer use in agriculture, livestock production, food production and processing, food retailing, and consumption. Some of these losses are avoidable, such as spillages, but others are unavoidable, such as losses in the form of crop residues, bones, and banana peels (75).

The situation is similar at the national level. An increasing number of national and regional phosphorus flow analyses indicate substantial phosphorus leakage/mismanagement (76–79). We illustrate four such national phosphorus flow analyses for Japan and Australia (**Figure 5**) and for Turkey and Zimbabwe (**Supplemental Figure 1**). These highlight the similarities and differences with respect to implications for phosphorus management. The largest reported phosphorus losses

Supplemental Material


a
Japan
173
Food and feed
103
Human
54
17
Livestock
Miscellaneous drainage
43
145
92
16
Fertilizer industry
401
Farm/ranch
43
40
River/coastal area
151
Fertilizer
151
Sludge
219
15
155
Chemical substance
155
376
Landfill
110
Phosphate ore
110
Chemical industry
Soil accumulation
24
24
Domestic products
Other industry
89
Products/ byproducts
23
67
Other mineral resources
113
Iron and steel industry
5
Steel
157
93
Slag
b
Domestic mines
288
1
Mining waste
Phosphate rock imports
64
Phosphate rock 353
11
25
0.02
Other losses
256
28
Fertilizer imports
149
Fertilizer 405
20
Phosphogypsum stockpiles
34
Fertilizer exports
Industrial uses (e.g., detergents)
180
203
6
Livestock Pastures, feedlots 257
27
Agriculture (soil, crops) 241
77
10
Vegetation
X
102
68 (H1)
27
Non-agri soil
Wild animals
X
Food/fiber production 182
100
Exported food/fiber
Imported food/fiber
1
Fisheries
53
1
15
12
6
Nonfood
Organic waste
12
Consumed food 12
7
Human excreta
12
Wastewater
2
Australia
9
0.2
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Water
12
Landfill

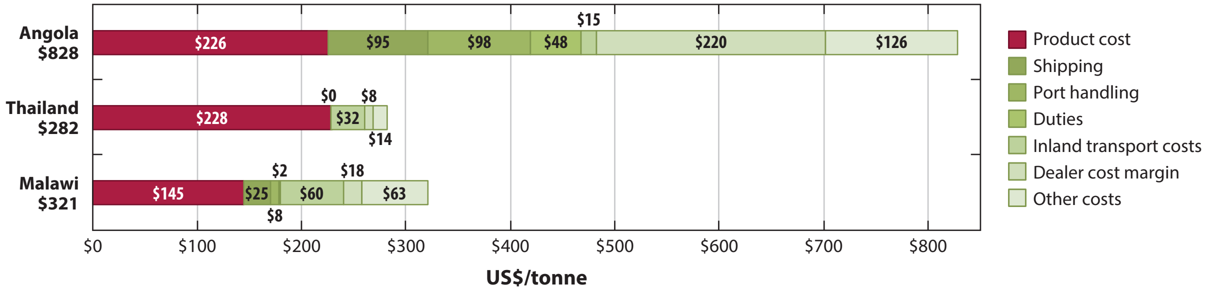

Figure 6

Farm-gate fertilizer costs comparing Angola, Thailand, and Malawi, broken down by product cost and additional transport and retail costs (data source: 87).

tended to be diffuse leakage from agricultural land—up to 66% in the case of the United States (78)—and point source loss as treated effluent from the wastewater sector (79). In Zimbabwe, the magnitude of phosphorus losses from soil via runoff was equal to that in the application of phosphate fertilizers (excluding manure) (80). However, country-specific differences were also evident. For example, over a quarter of phosphorus exports from the Netherlands were associated with bone meal for porcelain (77), whereas the export of live sheep and cattle in Australia represents up to a third of total phosphorus losses from the food system (81). In Japan, the iron and steel industries are major sources of phosphorus in the slag by-product (82). Such studies can assist in identifying priority intervention points to reduce losses and increase recycling to move toward a more closed-looped anthropogenic phosphorus system (83, 84).

2.3. Economic Scarcity

Lack of access to phosphorus due to limited financial capacity or constraints in labor and time can substantially contribute to apparent phosphorus scarcity. All farmers require access to phosphorus to maximize crop yields and sustain their livelihoods, yet up to a billion poor farming families currently do not have sufficient access to fertilizer markets because of low purchasing power or because they do not have access to credit (85, 86). The farm-gate cost of fertilizers can also vary widely from country to country (**Figure 6**) owing to margins associated with transport, handling, duties, and even corruption in some regions (87). African farmers in some landlocked countries can pay 2–5 times more than European farmers for fertilizers (88, 89), largely because of high freight costs, which can represent 20–30% of the retail price, especially when transport infrastructure is inefficient or in a state of disrepair (87). The 2008 commodity price spike for fertilizers and fuel shifted more farmers into phosphorus insecurity (47, 90, 91).

Current fertilizer demand represents only those farmers with purchasing power. There is a large silent demand from poor, small-scale farmers, particularly in sub-Saharan Africa, who are working with phosphorus-deficient soils and low crop yields (5, 92). For example, in Ethiopia, 44% of farmers do not use fertilizers, largely because they do not have access to cash/credit to

Figure 5

National phosphorus flow analyses for (*a*) Japan and (*b*) Australia, indicating major flows of phosphorus between sectors, losses, and imports and exports. (*Black arrows with numbers* = flows of phosphorus in kilotonnes per year; *black boxes* = sectors; *dotted line* = boundary of food system; *colored square* = national boundary.)

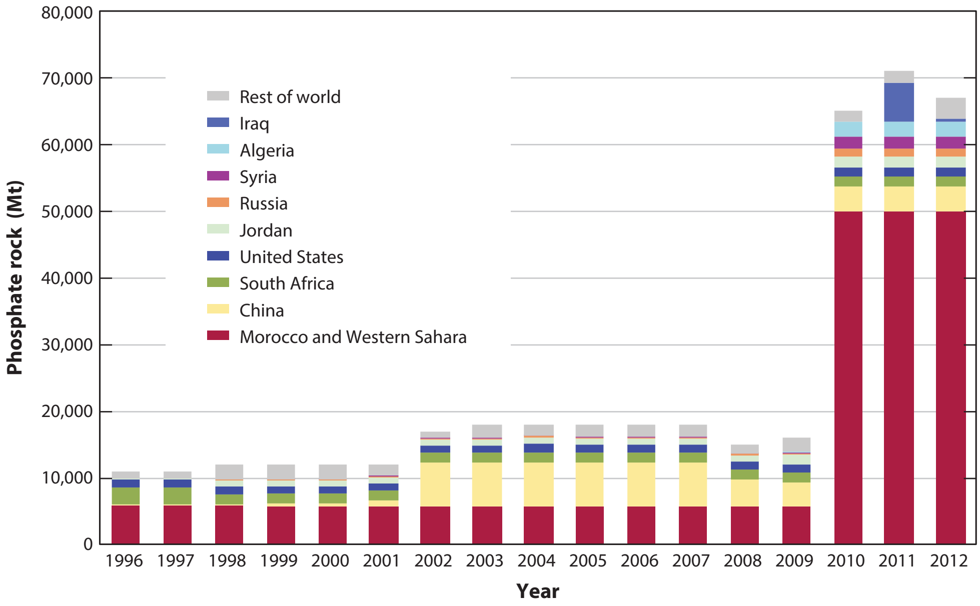

Figure 7

Breakdown of reported phosphate rock reserves by country, indicating both market concentration and how reported estimates have changed over time. In 2013, most reported reserves were controlled by Morocco, China, Algeria, Syria, Jordan, and South Africa. Data source: USGS Phosphate Rock Mineral Commodity Summaries 1996–2013 (**http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock**).

purchase them or they do not perceive them to be profitable given current input prices, soil, and rainfall patterns (85). According to a 2007 report published by the IFDC (87), in addition to limited access to finance and inefficient transport infrastructure (road and rail), economic and institutional barriers restricting the availability of fertilizers in Africa include nonconducive policy environments, ineffective regulation, inadequate human capital, restricted multicountry trade, inadequate market transparency and linkages, and inefficient port-handling facilities.

2.4. Geopolitical Scarcity

The uneven geological distribution of phosphate rock and significant geopolitical risks associated with such market concentration may restrict future availability of phosphate resources. Although over 35 countries have reported reserves (93), just six countries control 90% of the world's remaining high-grade phosphate rock reserves (**Figure 7**; 61). Morocco alone controls a reported 74%, all of which is run by state-owned Office Chérifien des Phosphates (OCP). A concern is this could encourage monopolistic behavior such as price-setting (47). Furthermore, the recent Arab Spring highlighted the potential risks of a supply or export disruption due to political unrest in major producing countries (47, 94, 95).

Some of these large reserves are in Western Sahara, a territory currently occupied by Morocco. Some sources estimate 10% of Morocco's production comes from Western Sahara (96); however, there are no official public statistics on reserves. Morocco's control and ownership of the territory and its phosphate deposits are contrary to UN resolutions (97), are contested by the independence movement (Polisario Front), and are not recognized by any African nation (98). This geopolitical situation presents both a risk to supply disruption and concerns over ongoing human rights abuses that importing companies, countries, farmers, and food consumers are knowingly or unknowingly supporting (47). Many Scandinavian companies have now divested from companies importing phosphate from the occupied region of Western Sahara (99).

In terms of annual production, China, the United States, Morocco, and Russia together produce 75% of the world's annual phosphate rock (61). This market concentration of major producing countries creates short-term risks and means all importing countries are vulnerable to the decisions of a few. For example, China shocked the world in 2008 by suddenly imposing a 135% export tariff on phosphate rock. This effectively halted exports from this major producer overnight and is thought to have contributed to the 2008 price spike (100).

2.5. Institutional Scarcity

Given that phosphorus underpins the world's food systems, there is a stark lack of effective global governance of the crucial resource. That is, there are no explicit international or national policies, guidelines, strategies, or organizations to ensure long-term availability and accessibility to phosphorus for food security (19, 41). Furthermore, no independent monitoring or accountability mechanisms address legitimacy and transparency. For example, despite the importance for farmers and policy makers, data and knowledge of the world's remaining phosphate rock reserves are not independently produced or managed; they are typically generated by mining and fertilizer companies and market analysts and are not sufficiently transparent, reliable, or publically available (41).

The management of phosphorus is currently fragmented among many disparate sectors in the food system with no overall coordination. For example, although phosphorus physically flows from the food we eat to our urine and feces, there is a huge disconnect between the food and sanitation sectors. Phosphate resources by default are governed by the market system. This may be sufficient to govern a narrow component of the system, such as efficiency of trade, triggering new exploration and technical advances (55). However, the market alone is ill-equipped to manage such an unevenly distributed yet critical resource in an equitable, timely, and sustainable manner. The market price of phosphate reflects its economic value (as a fertilizer) and does not reflect the true sustainability costs of mining and using phosphorus (19). The ecological and social costs are not valued, such as the increasing carbon cost of mining lower-grade phosphate, the ecological cost of eutrophication and pollution, its finiteness, and the social cost of the exploitation of Western Sahara.

Indeed, phosphorus scarcity can perhaps be attributed more to governance failures than to physical scarcity of the resource base (19, 101). The roles and responsibilities are currently unclear, including the role of the United Nations (particularly the Food and Agriculture Organization) and the social responsibility of the fertilizer industry (102). However, the first evidence of international phosphorus governance can be seen in the formation of the European Sustainable Phosphorus Platform (**http://www.phosphorusplatform.eu**) and European Commission consultation on Sustainable Phosphorus Use (95).

3. IMPLICATIONS OF THE CURRENT PHOSPHORUS USE TRAJECTORY

3.1. Future Global Phosphorus Trends

If no significant changes are made to the way phosphorus is currently used, the one-way flow of fossil phosphate from mines to oceans is likely to continue, exacerbating the current phosphorus challenges and vulnerabilities outlined in Section 2. Other emerging global sustainability

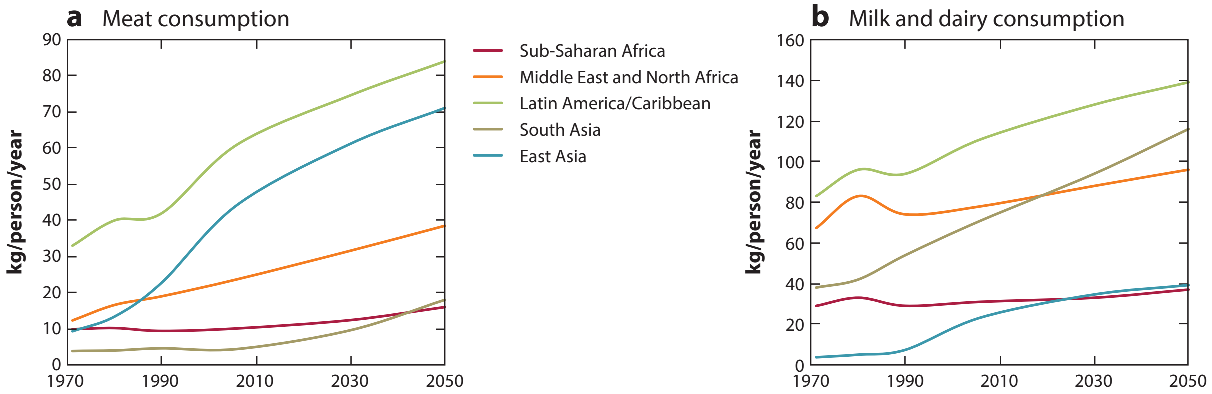

Figure 8

Per capita dietary changes in meat and dairy by region, 1970–2050 (data source: 108).

challenges and drivers are also likely to influence and be influenced by the world's phosphorus-use patterns (103), including pressures on the global food system and limits on arable land; population growth; changing diets; climate change, including increased climate variability; water scarcity; and the impacts of climate change on soil functioning and fertility (104).

For example, demand for phosphate is expected to increase due to changing population, changing diets, climate change policies, and the silent demand in Africa. An expected population of 9–10 billion by 2050 (105) means more mouths to feed and hence more fertilizers to grow crops, largely expected through intensification rather than extensification (106, 107). It is well understood that dietary preferences are shifting toward more meat and dairy products associated with increased affluence in emerging economies (**Figure 8**). If this continues, per capita meat and dairy consumption will continue to increase the per capita demand for phosphate. In addition, the nonfood demand for phosphorus is also likely to increase, due for example to climate change policies such as growth in first-generation biofuel crops that require fertilizers or to lithium-iron-phosphate batteries for electric vehicles that require 60 kg of phosphate per battery.

In a business-as-usual scenario, fertilizer prices are expected to increase as physical scarcity increases—that is, as input costs increase and phosphate grade declines (55). Higher phosphate prices in turn will continue to trigger new exploration and development of phosphate rock mines. Since the 2008 price spike, new mines have been developed or are proposed in Morocco (55), off the coast of Namibia (**http://www.namphos.com**), in the Georgina Basin of Australia (109), and in Saudi Arabia (47). These developments have increased the reported phosphate rock reserves (61). However, mining these future reserves will be constrained by thermodynamic realities (as noted in Section 2.1), and these new reserves contain less phosphorus (P_2O_5) and more impurities, such as cadmium and radionuclides. In some cases, they are also physically harder and more costly to access, such as the off-shore Namibian development that involves sea bed mining (55, 75, 110).

Furthermore, future long-term fertilizer price increases coupled with potential short-term price spike shocks are likely to affect the world's most vulnerable poor farmers first. A lack of institutional diversity governing phosphorus increases the potential for oligopolistic behavior and repeats of the 2008 price spike. The market system and power of key producing nations will continue to be the default governance system of phosphorus, leading to higher prices and potential disruptions to supply, further increasing the vulnerability of importing countries and of poor farmers (111).

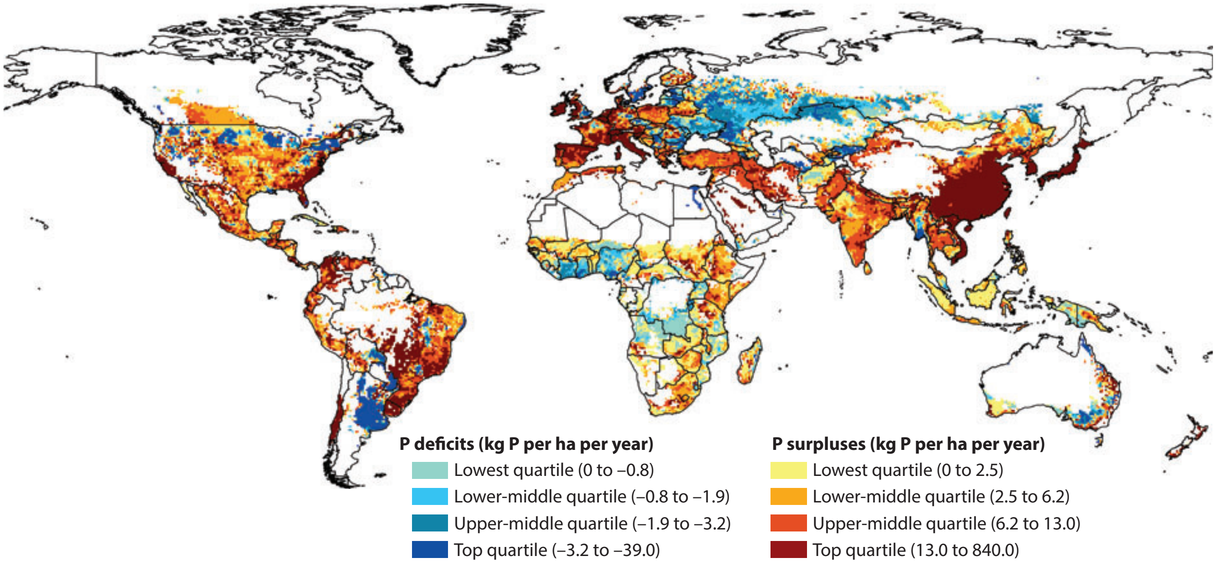

Figure 9

Uneven distribution: phosphorus use deficits and surplus around the globe, including fertilizer and manure application to agricultural soils (reproduced with permission from Reference 112).

If no action is taken to address phosphorus scarcity, a hard-landing situation is likely to result in increased energy costs for mining and processing phosphate, increased production and transport costs, increased generation of pollution and waste, long-term fertilizer price increases, further short-term price spikes, increased geopolitical tensions and risks, reduced farmer access to fertilizers, reduced global crop yields, and increased global hunger.

3.2. Phosphorus Paradox: Regional Dichotomies in the Phosphorus Challenge

Phosphorus is now understood as simultaneously scarce and polluting; both global problems are worsening (e.g., 52). Huge regional phosphorus disparities exist that are also likely to be exacerbated in the future without changes to the way phosphorus is used and governed by stakeholders throughout the food system. The distribution of phosphate rock is highly uneven geographically, and market share of production is likely to become even more concentrated in northern Africa in the long term (64, 68, 94), thereby exacerbating inequalities and the vulnerability of importing countries.

Some of the world's soils have a surplus of phosphorus, while others are phosphorus deficient due to both biogeochemical and anthropogenic causes (**Figure 9**; 112). This is evident on a global scale; for example, in Asia application rates can be as high as 196 kg/ha of fertilizer, whereas in sub-Saharan Africa typical rates average 5 kg/ha (52). Such uneven distribution is also evident within a single country. For example, in Australia, which has naturally phosphorus-deficient ancient weathered soils, many southern cropping systems now have a phosphorus surplus, whereas the vast northern grazing systems are over 90% phosphorus deficient (81). Even within a single farm, phosphorus can be unevenly distributed if, for example, animals defecate under a tree while seeking shade or while waiting in crowds during herding/milking (113).

Partly as a consequence of these disparities, coupled with the degree of fertilizer access, for some farmers the biggest phosphorus issue is managing excess, whereas for others it is securing

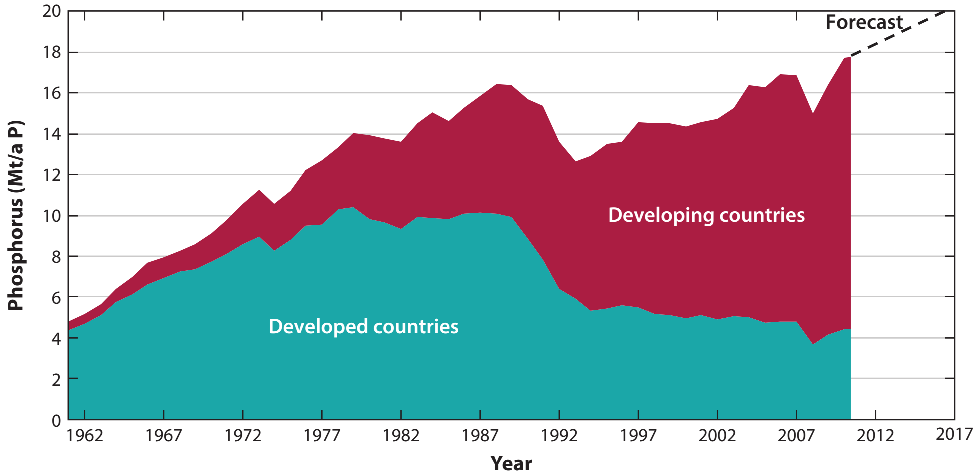

Figure 10

Global demand trends for phosphate fertilizers (1961–2017) broken down by developing and developed countries, indicating a stark decline in demand post-1989 in developed countries and a steady increase in developing countries, leading to an overall global increase. Data sources: historical (116) and forecast (117).

enough access to phosphorus fertilizers (114). This difference has fundamental implications for prioritizing phosphorus management strategies and interventions.

Demand for phosphorus fertilizers in the developed world is in decline as many soils have surpassed optimal phosphorus soil levels, while demand is growing more rapidly in developing and emerging economies where soils are often below optimal phosphorus levels and food productivity is increasing, requiring more fertilizers (29) (**Figure 10**). The sharp decline in global fertilizer demand after 1989 was attributed both to the collapse of the Soviet Union, a previously significant phosphate consumer, and to persistent changes in fertilizer application in North America and Western Europe associated with increased awareness of overapplication and links to water pollution (65, 115).

As of 2008, more global citizens are living in urban areas than rural areas (118). This urbanization trend is set to increase and has implications for phosphorus use and management, in addition to other social and environmental pressures such demographic shifts create. Cities are both phosphorus hotspots in human excreta and food waste (5) and in food demand. This dual pressure presents both a challenge and an opportunity in terms of urban food security, phosphorus pollution, and urban and peri-urban agriculture.

Some countries, such as Denmark, have a net excess of phosphorus, e.g., in manures/excreta (75), whereas other countries, such as Australia, have a net loss of phosphorus due, for example, to agricultural/food exports and leakage exceeding inputs (81). Again, this has significant implications for a food system's phosphorus vulnerability and priority strategies around investing in recycling or other efficiency measures.

The phosphorus inequity is most evident on the African continent: Despite having a near monopoly on the world's remaining phosphate rock, the continent is also home to some of the world's most phosphorus-deficient soils, poorest farmers, most costly farm-gate fertilizer prices, lowest fertilizer application rates, and highest food insecurity (5, 92).

4. SUSTAINABLE STRATEGIES FOR FOOD SECURITY AND ECOSYSTEM INTEGRITY

In an era of unprecedented global environmental change (119), flexibility, diversity, and long-term time frames will be essential for understanding, managing, and adapting our currently unsustainable and complex systems in a timely manner. To respond to the complex, paradoxical, and multiple dimensions of phosphorus scarcity and pollution, coexisting goals of national phosphorus security can be defined as (27, 41)

- Agricultural productivity: Increase overall phosphorus use efficiency of the food system (beyond the farm) by increasing the number of people fed per tonne of phosphorus input, or reduce total phosphorus demand while maintaining food/agricultural output;
- National security: Reduce dependence on phosphorus imports through diversification of sources, to buffer against price fluctuations and geopolitical risks in producing countries;
- Soil fertility: Ensure soils are fertile in terms of total bioavailable phosphorus, the carbon:nitrogen:phosporus ratio, organic matter, and moisture (92, 120);
- Farmer livelihoods: Ensure farmers' needs are met by ensuring access to sufficient phosphorus fertilizers in a bioavailable and manageable form (121);
- Environmental integrity and productivity: Reduce losses and wastage of phosphorus throughout the food system, from mine to field to fork (75); and
- Ecological integrity: Reduce eutrophication and pollution of rivers, lakes, and oceans (40).

These multiple goals can be achieved through several measures. Sustainable management of phosphorus has historically focused on phosphorus use efficiency in agriculture (driven largely by leakage/pollution or farm economics) (113) and phosphorus removal from wastewater (driven by pollution or wastewater management effectiveness) (27, 122). However, it is likely that meeting long-term global food demand through sustainable means will require an integrated approach that employs a suite of measures, as conceptualized in **Figure 11** (27, 69). **Figure 11** and **Tables 2** and **3** systematically identify a range of 35 demand-side measures (efficiency and changing diets) and 36 supply-side measures (reuse and new sources of phosphate rock) that can be implemented at all stages and sectors from mine to field to fork. For example, phosphorus can be potentially recovered from almost any waste stream—ranging from human excreta to crop residues to phosphogypsum (a fertilizer by-product)—and by any process—ranging from direct use to precipitation to incineration. Similarly, phosphorus losses and wastage can be reduced in all sectors, ranging from improving mining efficiency to improved fertilizer placement to reducing food waste. Overall, phosphorus demand can also be reduced through reducing overconsumption of meat and dairy products.

A systematic overview of potential supply- and demand-side measures in different sectors can be found in Cordell & White (27), Cordell et al. (69), and Childers et al. (123, 124). A range of phosphorus use efficiency measures in agriculture are summarized in different European, African,

PHOSPHORUS SECURITY

A sustainable phosphorus system ensures that phosphorus is not only available in the long-term, but also accessible. Phosphorus security is therefore defined as ensuring that all farmers have short- and long-term access to sufficient phosphorus to produce food to feed the global population, while ensuring ecosystem integrity and sustainable livelihoods (41).

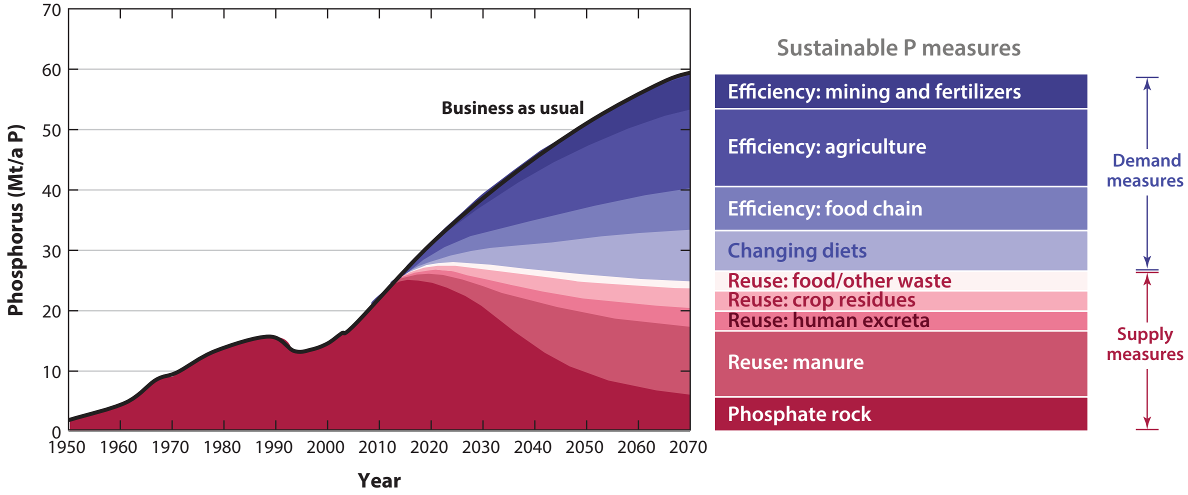

Figure 11

Possible long-term integrated supply-side and demand-side measures for meeting future food security of 9 billion people (data sources: 27, 69).

and Australian contexts in Schröder et al. (113), Smaling et al. (125), and Simpson et al. (126), respectively. Sartorius et al. (127), Rittmann et al. (128), and Cordell et al. (122) review phosphorus recovery measures.

However, what works in one country or region might be inappropriate or ineffective in another. A phosphorus vulnerability assessment (111) can assess the nature and pathways by which a given food system is susceptible to harm owing to the different dimensions of phosphorus scarcity and pollution, including the degree of sensitivity and capacity to cope or adapt. This in turn can inform priority adaptive strategies to increase the resilience of that particular country or food system (129). For example, Europe is a region dependent on imported phosphate, yet also has excess phosphorus in manure, limited land on which to spread the manure, and stringent water quality regulations that limit phosphorus discharges [such as the Water Framework Directive (130)]. This means recovering phosphorus for reuse is a priority (95). India, by contrast, is 100% dependent on phosphate imports and yet is the largest phosphorus fertilizer consumer in the world (26), with relatively low farmer livelihood security and with increasing fertilizer demand. This means India may need to prioritize fertilizer access and diversify sources of phosphorus. Australia, a net food producer, has naturally phosphorus-deficient soils yet has invested heavily in phosphate-intensive agricultural export industries such as beef, wheat, and live exports, resulting in a net export of phosphorus (81). This means even recycling 100% of phosphorus in human excreta in Australia would at most meet 5% of the country's total phosphorus fertilizer demand, and hence sustainable phosphorus measures such as efficiency in agriculture must be a priority.

Finally, in addition to identifying sustainable strategies to address both phosphorus scarcity and pollution, there is a need to consider broader interactions, synergies, and trade-offs with other sustainability challenges, such as climate change, energy scarcity, water scarcity, and their associated initiatives, such as climate change mitigation and adaption policies (103). Considering these in isolation may indeed result in unintended consequences or inefficient outcomes (122). For example, Hein & Leemans (131) found that the negative impact of first-generation biofuels (a promising climate change–mitigation measure) on the depletion of phosphate was compromising

Table 2 Toolbox of demand-side phosphorus measures from mining to agriculture to sanitation (27)

Sector	Demand-side sustainable phosphorus measures	
	Efficiency	**Reduce demand**
Mining	Reduce avoidable losses	NA
Fertilizer	Reduce avoidable losses	NA
Agriculture	Fertilizer placement Application time Application rate Soil testing Erosion reduction Microbial inoculants	Plant selection Improved soil characteristics
Livestock and fisheries	Fertilizer placement Application time Application rate Soil testing Erosion reduction Microbial inoculants Phytase enrichment Manure phosphorus reduction Wastewater management	Plant selection Improved soil characteristics Animal selection Changing diets
Food production	Reducing avoidable losses Producing food closer to demand Consumer food planning/preparation	Reducing phosphorus-intensive diets Reducing per capita overconsumption Healthy bodies Minimizing use of phosphorus additives
Wastewater & human excreta	Repairing cracked pipes minimizing sewer overflows Soil management Avoiding dumping of biosolids in Oceans/rivers Reducing spreading of biosolids on nonagricultural land	NA

NA, not applicable.

future food production. This stressed the need for an integrated approach, seeking positive synergies identifying trade-offs.

Examples of synergistic measures might include community-scale biogas generation from human and animal excreta that not only provides sanitation services but also generates biogas for cooking and sludge for local fertilizer use (122). Other examples of initiatives that provide cobenefits include the production of algae using nutrient-rich effluent (132) and a shift toward plant-based diets to reduce greenhouse gas emissions and water and fertilizer demand (133, 134). However, it is important that these measures be implemented without imposing high additional costs on society (taking account of social and environmental costs and benefits) compared with the current practice. Linderholm et al. (135) compared the life cycle energy use, greenhouse gas emissions, and eutrophication impacts of mineral fertilizers to three different phosphorus recovery systems sourcing phosphorus from the wastewater sector: sewage sludge, struvite, and sewage incinerator ash. The authors found that the most energy-efficient and low greenhouse gas–producing phosphorus reuse option for the Swedish context was sewage sludge.

Table 3 Toolbox of supply-side phosphorus measures from mining to agriculture to sanitation (27)

Sector	Recycling: Source	Recycling: Process	New source (renewable or finite)
Mining	Mine tailings	Chemical treatment	Phosphate rock
Fertilizer	Phosphogypsum	Chemical treatment	Algae, seaweed
Agriculture	Crop waste	Compost, incineration, fermentation	Green manure
Livestock and fisheries	Manure	Direct reuse, compost, dewatering	Phosphate rock (supplements)
	Bone	Direct reuse, incineration	
	Blood	Direct reuse	
	Fish	Direct reuse	
Food production	Food production waste Cooked food waste		Phosphate rock (additives)
Wastewater and human excreta	Urine	Direct reuse, precipitation	NA
	Feces	Compost, precipitation, incineration, chemical treatment	
	Gray water	Precipitation, chemical treatment	
	Untreated wastewater	Direct reuse	
	Treated effluent	Direct reuse	
	Struvite	Precipitation	
	Biosolids	Direct reuse, compost, fermentation, chemical treatment	
	Sludge ash	Dewatering	

NA, not applicable.

Implementing such measures requires enabling institutional environments. From a policy perspective, this requires decision makers to consider a range of institutional barriers and to develop policy tools that can address these barriers (27). Research in other fields including energy resource management can provide a useful framework for a typology of barriers and policy tools, as shown in **Figure 12**.

Examples of options that span the range of policy instruments include the following:

- Targets: For example, Sweden has a requirement that 40% of the phosphorus from sewage be recycled (137). As a future example, the post-2015 Sustainable Development Goals could incorporate phosphorus use targets (4).
- Information: For example, the Digital Soil Map of sub-Saharan Africa aims to provide "up-to-date information on the health and properties of the soil, helping farmers and policymakers to improve degraded soils and increase crop production" (138).
- Facilitation: For example, there are several recent sustainable phosphorus platforms, including the European Commission's consultation on phosphorus and the Sustainable Phosphorus Platform (**http://www.phosphorusplatform.eu**) and the many national or stakeholder-driven initiatives, such as the Global Phosphorus Research Initiative (**http://www.phosphorusfutures.net**), the Dutch Nutrient Platform

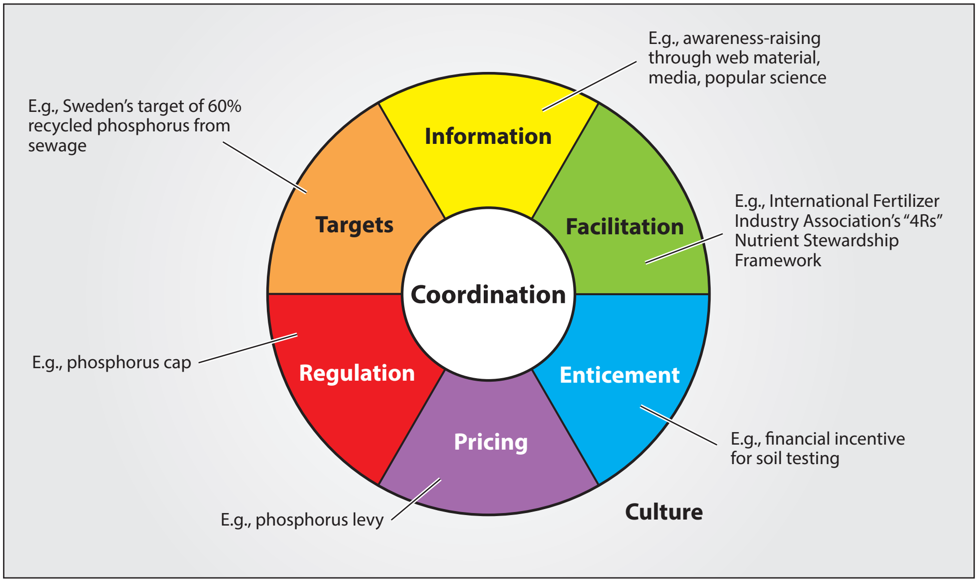

Figure 12

Policy palette indicating potential policy instruments and examples for phosphorus (data sources: 27 after 136).

(**http://www.nutrientplatform.org**), Global TraPs (**http://www.globaltraps.ch**), and the dedicated Sustainable Phosphorus Summits (**http://sps2014.cirad.fr**).

- Regulation: For example, the EU Water Framework Directive (130) sets limits on phosphorus discharge to waterways. Future examples could include cap-and-trade provisions for phosphorus use, similar to those for carbon, incorporating the principles of contraction and convergence (19).
- Pricing and economic incentives (enticement): For example, policy makers and industry must ensure that the market price reflects the true cost of phosphorus mining, production, and use, including its nonrenewable nature, through pricing in the externalities, or a Hotelling tax (139). This may require economic incentives and taxes to stimulate more sustainable phosphorus sources (e.g., 140).

Developing a priority phosphorus strategy requires substantial engagement of stakeholders and citizens, as well as of experts in the field, not only to ensure scientific credibility but also to increase the public policy saliency and legitimacy of the process and outcomes (141). Futures methods, including foresighting (142) and systems thinking (143), are potentially useful tools for determining the appropriate mix of policy tools to implement.

5. CONCLUSION

The accelerated flow of phosphate rock from Earth's crust for fertilizer use has been both a blessing and a curse for food security and the environment, by boosting crop yields yet simultaneously leading to widespread water pollution and creating a precarious dependence of the world's food systems on a single source of phosphorus. The consequences of phosphorus scarcity will occur long before the last megatonne of phosphate rock is mined. The current phosphorus demand trajectory imposes a range of types of scarcity, not limited to its physical scarcity. If this current trajectory is not altered, phosphorus scarcity is likely to have serious consequences for food security, reduced agricultural productivity, and smallholder farmer access to fertilizers and food, particularly in developing countries. Future-oriented and systems frameworks can guide identification of priorities to increase resilience of food systems. Conversely, not doing so can result in perverse outcomes and investment in ineffective or insufficiently sustainable phosphorus strategies.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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