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Review

Peak Phosphorus: Clarifying the Key Issues of a Vigorous Debate about Long-Term Phosphorus Security

Dana Cordell and Stuart White *

Institute for Sustainable Futures, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia; E-Mail: Dana.Cordell@uts.edu.au

* Author to whom correspondence should be addressed; E-Mail: Stuart.White@uts.edu.au; Tel.: +61-2-9514-4950; Fax: +61-2-9514-4941.

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Abstract: This paper reviews the latest information and perspectives on global phosphorus scarcity. Phosphorus is essential for food production and modern agriculture currently sources phosphorus fertilizers from finite phosphate rock. The 2008 food and phosphate fertilizer price spikes triggered increased concerns regarding the depletion timeline of phosphate rock reserves. While estimates range from 30 to 300 years and are shrouded by lack of publicly available data and substantial uncertainty, there is a general consensus that the quality and accessibility of remaining reserves are decreasing and costs will increase. This paper clarifies common sources of misunderstandings about phosphorus scarcity and identifies areas of consensus. It then asks, despite some persistent uncertainty, what would it take to achieve global phosphorus security? What would a 'hard-landing' response look like and how could preferred 'soft-landing' responses be achieved?

Keywords: peak phosphorus; global phosphorus scarcity; depletion; global food security; phosphate rock; phosphorus security

1. Introduction

While the element phosphorus (P) is one of the fundamental building blocks of life and essential for food production, there has been very little research on the implications of future phosphorus scarcity for global food security. Ensuring long-term availability and accessibility of phosphorus sources is critical to the future of humanity [1] yet unlike water and energy scarcity, this topic has been largely ignored in research and policy debates on global food security and sustainable resource use until relatively recently. The short-term 800% price spike in phosphate rock and associated fertilizer commodities in 2008 triggered a sharp increase in interest in long-term phosphorus security from the media, policy-makers, farmers, scientists and response from industry and scientific and popular science articles [2].

There is little disagreement regarding the significance of phosphorus to life, and specifically humanity's dependence on phosphorus for food production. However the collective understanding of the nature of phosphorus scarcity is still embryonic and there are numerous sources of confusion, misinterpretation, lack of consensus and uncertainly regarding key issues. This paper aims to clarify some of the sources of misunderstandings and lack of consensus, thereby contributing to clarification of the nature of global phosphorus scarcity. This paper achieves this goal by reviewing and synthesizing the recent body of research on global phosphorus scarcity and sustainable future pathways, drawing both from the authors' own and others' research.

2. Phosphorus: Life's Bottleneck

The critical life-giving properties of the element phosphorus are reasonably well understood today. There is relatively little disagreement among scientists, industry and scholars as to the key features of phosphorus (Box 1).

Box 1. Life's bottleneck: Key features of a critical element, phosphorus:

- phosphorus is essential for all life, including plants, animals and bacteria–it is a fundamental component of DNA, RNA and ATP responsible for energy transport to the brain;
- There is no substitute for phosphorus in crop growth and therefore in food production;
- phosphorus cannot be manufactured (or destroyed);
- phosphorus is a limiting nutrient in crop growth and hence can limit global crop yields;
- phosphorus is the 11th most abundant element in the earth's crust, yet practically useful deposits are geographically concentrated in only a few countries;
- unlike the other fundamental elements underpinning life (carbon, nitrogen, oxygen and hydrogen), phosphorus has no significant gaseous phase and cannot circulate freely in the atmosphere;
- As long as humanity exists, there will always be a global demand for phosphorus.

In short, there is no substitute for the element phosphorus in the growth of all living organisms. While other critical global resources, such as oil, can be replaced with renewable energy sources, such as wind or solar power, no other element can replace phosphorus in food production.

Phosphorus was chemically identified over 300 years ago. In the late 17th Century the German alchemist Henning Brandt distilled 50 buckets of urine through heating and evaporation in search of the legendary 'Philosopher's Stone' which would supposedly turn metal into gold [3]. Whilst he found no such magical stone, Brandt discovered the pure form of phosphorus, which also glowed in the dark and was highly flammable.

However it was only when the German chemist Liebig discovered phosphorus was a limiting nutrient in plant growth in 1840 that phosphorus became routinely used in mineral fertilizers. Prior to Liebig's discovery, crop production relied on natural levels of soil phosphorus with the addition of manure, crop residues and in parts of Asia human excreta [4]. After World Water II, phosphorus became one of three (N-P-K) essential nutrient ingredients in commercial fertilizers and was applied extensively worldwide [5]. Fertilizer use increased six-fold between 1950 and 2000 [6]. It has only been in the past few decades that the severe consequences of mobilizing excess nutrients into the environment (causing eutrophication and dead zones) became apparent [7].

Industrial agriculture dramatically altered the phosphorus cycle, by transporting harvested crops all over the world for food processing and consumption, unlike the natural biochemical cycle, which recycles phosphorus back to the soil via dead plant matter. This also meant that continual application of phosphorus-rich fertilizer was required to replace the soil with what was removed in harvest.

While there is little doubt today that phosphorus has played a significant role in feeding the world, humanity is effectively dependent today on phosphorus from mined phosphate rock. Without continual inputs we could not produce food at current global yields. While phosphate rock seemed like a plentiful source of highly concentrated phosphorus, humanity was, and still is, relying on a non-homogenous, non-renewable resource. Increasing environmental, economic, geopolitical and social concerns about the short and long-term use of phosphate rock in agriculture means there is a need to reassess the way crops obtain their phosphorus and humanity is fed [8].

3. Clarifying Common Misunderstandings about Phosphorus Scarcity

Whilst the critical nature of phosphorus in food production as highlighted above is not in doubt, there is much debate over the long-term availability of phosphate rock for meeting future global food demand. The main point of contention is the ‘timeline’ of remaining phosphate rock, or ‘million tons of reserves’. Some of the uncertainty is due to lack of data and research, other sources of contention is due to misunderstandings and oversimplifications of the situation, while other disagreements are again due to differences in fundamental principles and assumptions around which the arguments are based [8]. This section clarifies some of the sources of uncertainty and misunderstandings, thereby providing an improved understanding of the nature of phosphorus scarcity and possible sustainable future pathways in subsequent sections.

3.1. Phosphorus is not ‘Running Out’: Law of Mass Conservation

The terms “running out”, “shortage” and “scarcity” are fundamentally different, yet are frequently used interchangeably with reference to phosphorus in scientific journals, popular science magazines, newsletters and within the media [9]. However, the element phosphorus is not running out. According to the Law of Mass Conservation, phosphorus molecules cannot be created or destroyed. There are a fixed number of phosphorus atoms on the planet (meteors aside) and phosphorus cycles naturally between the lithosphere and hydrosphere, between land, biota and soil and between aquatic biota and aquatic sediments. Further, phosphorus is the 11th most abundant element in the earth’s crust (amounting to some 4,000,000,000,000,000 tons P), so not considered a geochemically scarce element. Clarity in this regard is therefore important for scientific credibility. Discussions regarding shortage or scarcity are related to the irreversible depletion of high-concentration rock phosphate reserves and the economic and energetic barriers to their exploitation as discussed in the next section.

3.2. Mineral Resource Terminology: Phosphorus, Phosphate, Phosphate Rock and Phosphate Reserves

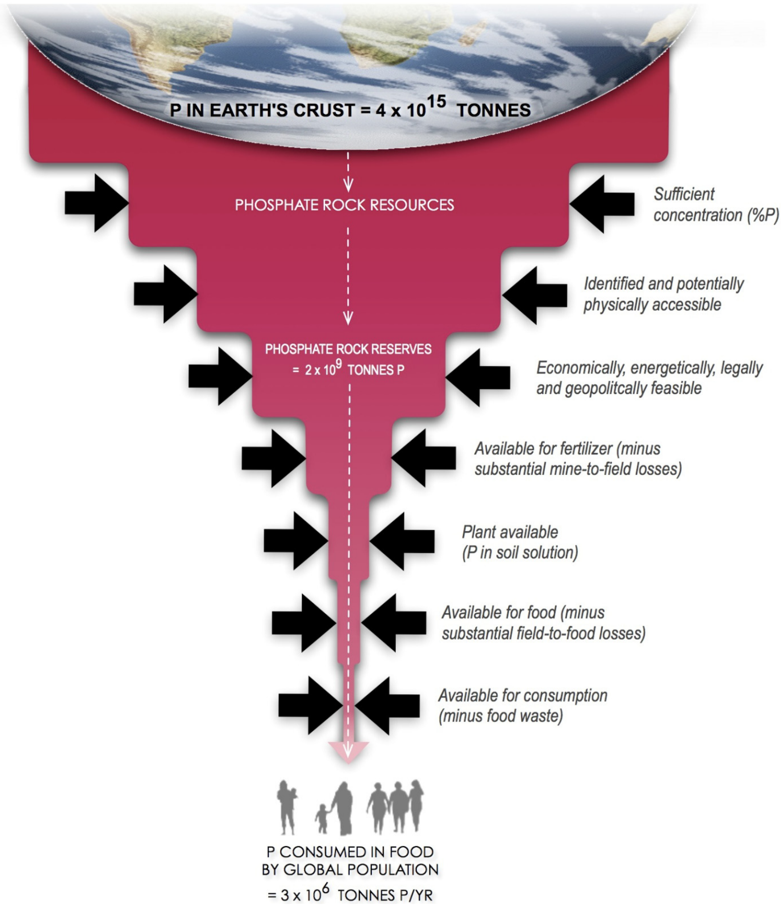
Recent misunderstandings have also arisen in part from inappropriate or vague use of the terms "phosphorus", "phosphate rock", "phosphate", "phosphate reserves", which are importantly not interchangeable. Distinguishing between these is important firstly in relation to substitutability: There is no substitute for the element phosphorus in the growth of all living organisms [10]. There is however a substitute for phosphate rock as a source of phosphorus fertilizer and other industrial applications. Phosphate rock has been the largest source of phosphorus fertilizers since the Second World War, however, it is not the only source of phosphorus [11].

Secondly, in relation to finite *versus* renewable resources: phosphorus is 'renewable' in the biosphere in the sense that it cycles between dead and living organisms (e.g., between plants and soil) at rates of 'days to years' (as described in 3.1). Hence organic sources of phosphorus such as crop residues, food waste, excreta are all considered 'renewable' sources of phosphorus. Phosphate rock on the other hand is classed as 'non-renewable', as it cycles between the lithosphere and hydrosphere at rates of 'millions of years'. Therefore the concentrated source of phosphorus in rock (phosphate rock) is considered non-renewable and hence finite.

Thirdly, it is important to distinguish between terms when quantifying these sources. Phosphorus is rarely found in its elemental form (P), and hence often measured by the phosphate mining and fertilizer industry as phosphorus pentoxide (P_2O_5), which contains 44% P. Phosphate rock is the term for naturally-occurring phosphorus-rich sedimentary or igneous rock, that typically contains around 5–13% P [5,11,12]. Naturally occurring phosphate rock is often upgraded to a rock production containing 11–15% P. This compares to the average phosphorus concentration of the earth's upper crust-approximately 0.1% P [5]. This means that, whilst phosphorus is abundant in the earth's crust (approximately 4×10^{15} tons of P total), only a small fraction of this (approximately 0.007%) is present in the concentrated form of phosphate rock resources. Phosphate rock *reserves*, is that portion of phosphate rock resources that have been deemed technically and economically feasible at current standards (today this represents around 20% of phosphate rock resources) [13]. The amount of reserves is therefore dynamic and variable from year to year, as it depends on current technology and prices. However, importantly, the quality of the reserves (such as % P and presence of impurities) is generally in decline over time. The newest estimates of phosphate rock by the International Fertilizer Development Center (IFDC) preliminarily estimate reserves to be 60,000 Mt of phosphate rock [13], a substantial increase on previous estimates by the US Geological Survey [14]—16,000 Mt of phosphate rock. The USGS has now updated their reserve estimated based largely on these IFDC estimates. This is largely due to revised reserve estimates for Morocco from 5,600 to 51,000 Mt of phosphate rock. However these figures are based on secondary literature from 1989 and 1998 and are still considered preliminary and highly uncertain by the IFDC author and other critics [13,15].

A fundamental point when measuring available phosphate in relation to food security, is that the amount of phosphorus available for productive use by humanity is orders of magnitude smaller than the amount of resources (or even reserves) estimated in the ground, due to a range of physical, ecological, technical, geopolitical, social and legal limitations or 'bottlenecks' (Figure 1). An analogy with water can be made: while freshwater is highly abundant on the planet (in lakes, rivers, glaciers, groundwater, aquifers), only a very small fraction is available for productive use in society (for irrigation, drinking, cooking, hygiene and industrial uses). Similarly with phosphorus, only a small amount will ever be available for use in food production and other industrial applications, yet there is a dramatic difference in understanding and awareness of phosphorus availability and accessibility compared to water.

Figure 1. Phosphorus bottlenecks: physical, economic, social and ecological factors limiting the availability of phosphorus for productive use by humans for fertilizers and hence food production. Units are in P. Widths are schematic and not to scale.



3.3. Depletion Scenarios versus *Peak Resource Theory*

Another common source of misunderstanding is the incorrect assumption that depletion estimates and peak phosphorus estimates are analogous. Depletion estimates are often simply derived by dividing the total reserves by an average annual consumption (or increasing annual consumption), to yield the estimated lifetimes of reserves [16]. Table 1 provides different estimated lifetimes of phosphate rock reserves based on different assumptions.

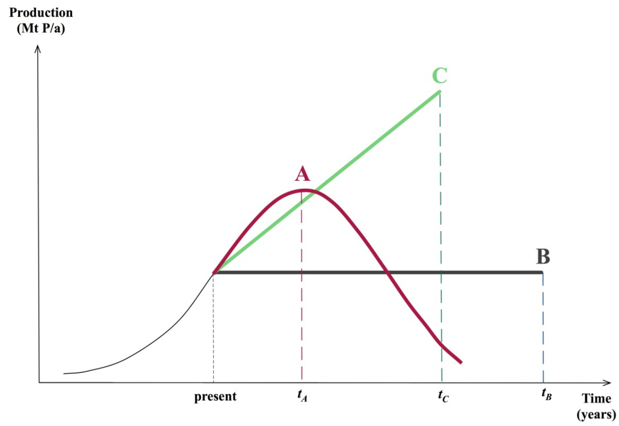
Peak resource theory (based on empirical evidence) postulates that a critical period (the so-called 'peak' in the production of the commodity) will occur long before 100% of the reserve is theoretically depleted. This is due to the non-homogeneous nature of the reserve and the economic and energy constraints of accessing the lower quality and more difficult to reach rock. The premises behind peak phosphorus are explained in detail in section 4. Figure 2 depicts the key differences between estimating the peak phosphorus timeline (A) and depletion scenario timelines (B & C).

Table 1. Estimates of lifetime of current world phosphate rock reserves by different authors.

Author	Estimated lifetime of reserves	Estimated year of depletion *	Assumptions
Tweeten [16]	61 years	2050	Assumes 3.6% increase in demand; in [19]
Runge-Metzger [17]	88 years	2083	Assumes 2.1% increase, based on 1992 World Bank/FAO/UNIDO/ Industry Fertilizer Working Group
Steen [18]	60–130 years	2058–2128	Based on range of 2–3% increase demand rates, plus a 'most likely' 2% increase until 2020 and 0% growth thereafter if efficiency and reuse measures are implemented.
Smil [7]	80 years	2080	At 'current rate of extraction'
Fixen [19]	93 years	2102	At 2007–2008 production rates
Smit *et al*. [20]	69–100 years	2078–2109	Assuming 0.7–2% increase until 2050, and 0% increase after 2050.
Vaccari [15]	90 years	2099	At 'current rates'
Van Kauwenbergh [13]	300–400 years	2310–2410	At 'current rates'

* year of depletion assumes lifetime estimated from date of publication.

Figure 2. Three different models for estimating the critical point in time when demand for phosphorus will exceed supply: A. peak phosphorus production, B. depletion scenario based on average annual consumption and C. depletion scenario based on an assumption of generally increasing average consumption. In each case, the area under the curve is equal to the total remaining reserves.



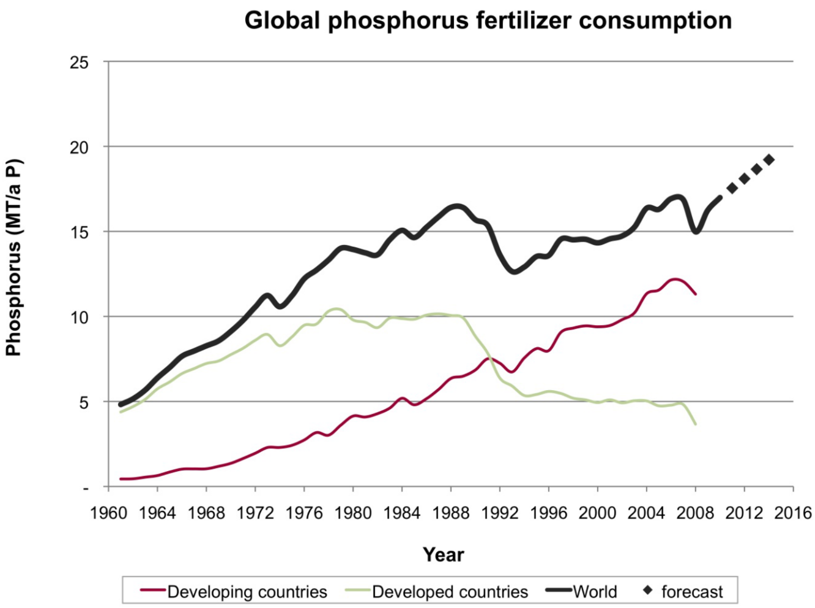
3.4. Uncertain Future Demand

On the consumption side, the future phosphorus demand trends are far from static. While the supply of high-grade cheap phosphate rock is likely to be constrained in the future for the reasons identified above, the overall demand for phosphorus is anticipated to increase. Although fertilizer demand is stabilizing in parts of Europe and North America, where decades of over-application means that soils are saturated and thus only require application to replace what is lost in harvest [21], the situation is quite different in developing countries and emerging economies. Global demand is forecasted to increase in the short-term on average around 3% until 2014/15, with around 2/3 of this demand coming from Asia [22,23] (see Figure 3). Long-term trends are less clear, but likely to see an increased demand due to various factors. Key factors likely to contribute to a net increasing future demand for phosphorus include:

- increased population growth (9 billion expected by 2050) causing a surge in food demand [22];
- per capita increased phosphorus demand due to changing dietary preferences towards more meat and dairy products (especially in growing economies like China and India), which require significantly more phosphorus fertilizer per capita [23,24].
- increasing demand for non-food crops like biofuels (energy crops require substantial amounts of phosphorus fertilizers to ensure high crop growth) [25] or lithium-iron-phosphate electric vehicle batteries, which can require 60 kg of phosphate per battery;
- The need to boost soil fertility in phosphorus-deficient regions. Industry projections of demand are often based on the current market demand, that is, those players with purchasing power. However there is a large 'silent' demand from poor farmers with phosphorus-deficient soils that cannot currently access fertilizer markets. In Sub-Saharan Africa for example, where at least 30% of the population is undernourished, fertilizer application rates are extremely low and 75% of agricultural soils are nutrient deficient thus yields are falling [26,27].

While improvements in efficiency in phosphorus recovery from mining may decrease demand for phosphate rock, it is likely that the factors placing upward pressure on demand would still outweigh these efficiency gains [24].

Figure 3. Global phosphorus fertilizer consumption between 1961–2006 (in million tons phosphorus, P). The figure indicates that while demand in the developed world reached a plateau and then declined around 1990, fertilizer demand has been steadily increasing in the developing world**.** Data: IFA DATA [25].



3.5. Inherent Data Uncertainty

Finally, the accuracy of phosphate reserve data is limited by the inherent uncertainty around phosphate rock data. There are substantial concerns regarding the scarcity of phosphorus data, including: a lack of raw data on phosphate rock reserves, data uncertainty, lack of accountability, lack of transparency of knowledge production and knowledge management and power imbalances between current data producers and data users. Of all sources of phosphorus (which include manure and crop residues), most data is available for phosphate rock. However, there is still a scarcity of reliable, transparent, independent data on phosphate rock reserves, resources, time series price trends and production, which warrants concern. This data is very important for estimating a timeline for peak phosphorus production (and other depletion scenarios) and short-term availability. Key aspects of phosphate rock data scarcity include:

- *Physical/geological*: Basic uncertainties associated with physically or technically estimating geological phosphate rock reserves and deposits at the exploration stage (such as extrapolating ore grades and other characteristics from the analysis of core samples from drill holes). The recent IFDC study based its conclusions on a 1989 and 1998 study which estimated reserves based on extrapolating phosphorus soil and rock concentrations in the Moroccan region [13];
- *Economic*: Inconsistent economic assumptions behind what constitutes a 'reserve'. USGS notes that each country/company uses different assumptions such as $/tonne;
- *Commercial*: Any data that does exist is typically produced by the mining and fertilizer industry and is often not publicly available due to 'commercial in confidence' reasons. In Australia, for example, the national government's geological center, Geoscience Australia, does not have a complete account of Australia's phosphate rock reserves and annual phosphate production because mining and fertilizer firms are not obliged to disclose such information [26];
- *Privatized knowledge*: Some commercial data is available, at very high cost. Knowledge production itself (often undertaken by the mining industry) is also not independent and transparent and assumptions can influence findings, such as how long current global phosphate reserves will last;
- *Institutional*: Currently, USGS is one of only a few organizations that produce publicly available commodity data on global minerals and metals. This means most analyses rely on USGS data and there is little opportunity to triangulate with other sources. The World Bank does produce phosphate rock price data as part of its *Commodity Price Data*, however these data sets (both 'real' and projected) for phosphate rock missed the 2008 price spike as it occurred [27];
- *Geopolitical*: For example, China's reported reserves doubled over night when it joined the World Trade Organisation. Further, in 2007, reported world reserves totaled 18,000 million tons, while in 2008 they decreased to 15,000 million tons, largely because China altered its reported reserves, and Australia increased its reserves moderately [12];
- *Analytical*: In some instances, data may exist but there is a lack of data collation and synthesis. For example, national data on phosphorus flows could be collated and synthesized from various countries and regions and used to extrapolate to the global scale.

While some of these sources of uncertainty and misunderstandings can be overcome (such as those related to terminology, methodology, some data collection), others will remain as inherent uncertainty (such as future trends, commercial-in-confidence data) and thus future sustainable pathways need to be developed around such risks and uncertainties.

4. Peak Phosphorus: Important Concept or Misleading Doomsday Scenario?

An important dimension of phosphorus scarcity, lies in understanding the critical period when supply will no longer be able to keep up with demand, so that a smooth transition may be planned for. The notion of peak phosphorus, in particular, has been hotly contested by scientists, industry, policy-makers, in recent years, particularly following the short-term price spike [1,11,28]. However, due to the embryonic nature of the field, peak phosphorus is still poorly understood. This section aims firstly to clarify the logic and premises behind the concept of the peak phosphorus curve, secondly to clarify the differences and assumptions behind the two key empirical peak phosphorus analyses that emerged in recent years, *i.e.*, [1,29,30] to finally to clarify the sources of much debate and confusion.

4.1. The Premises behind Peak Phosphorus Curve and Concept

While Hubbert [31] originally developed the peak oil curve empirically (that is, from aggregating oil reserve production data from the lower 48 States of the USA), the curve can be applied to estimate the peak year/period of reserves that have not yet peaked. Hubbert's analytical framework has since been applied to other non-renewable resources, such as other fossil fuels [32], other metals and minerals [32-34] and phosphorus [1,29]. Peak theory has also been applied more conceptually to renewable resources such as water [35], soils [36,37], food [38], and even to human resources such as population. A fundamental notion behind the broad use of peak theory in the above cases is that the growing demand for the critical resource (be it oil or fertile soil) will outstrip economically available supply (annual production) at some point, if left unchecked, despite some advances in technology and efficiency.

The concept and analysis of peak phosphorus is based on the following premises:

1. Phosphate rock is a finite resource that takes 10s to 100s of millions of years to cycle or 'renew' naturally;
2. Phosphate rock is non-homogenous resource, where the higher quality, more easily accessible layers are mined first;
3. As a result of 1 and 2 above, this means that over time, the average quality of phosphate rock is decreasing, in terms of P_2O_5 percentage (and also the increasing presence of impurities and heavy metals). This is also supported by empirical evidence [39];
4. Premise 3 means that increasing energy, resources, and costs are required per unit output of nutrient. That is, to extract the same nutrient content (e.g., P_2O_5) over time requires increasing inputs;
5. Premise 3 also means that extracting the same nutrient output generates more waste byproducts;
6. While the short and medium tern costs may fluctuate due to short term changes in demand or improvements in production methods, over the long term costs and energy inputs will increase, and indeed will increase not linearly, but exponentially as ore concentrations decline and will require an increasing amount of phosphate rock to be mined. Observable changes over time typically occur once approximately 50% of the resource has been consumed;

7. While there may be some fluctuations causing year-to-year variation in phosphate production (due to supply-side or demand-side variables), there will always be a global demand for phosphorus, as argued in section 2);
8. This means at some critical point, the increasing annual production of phosphate rock will become unviable due to increasing energy, economic and other constraints, while demand will continue to increase.

A key significance of peak phosphorus analysis is that the critical point in time is not when 100% of the reserves are depleted, but much sooner than this. This means, preparing for a soft-landing will need to take this timeline in to account, given that most measures (such as those outlined later in section 7 and [40]) will take decades to be implemented. It must be re-iterated here that farmers need both annual and long-term access to phosphorus fertilizers in order to achieve high crop yields. If no action is taken decades before the anticipated peak, a hard-landing response to peak phosphorus is likely to result in a situation of:

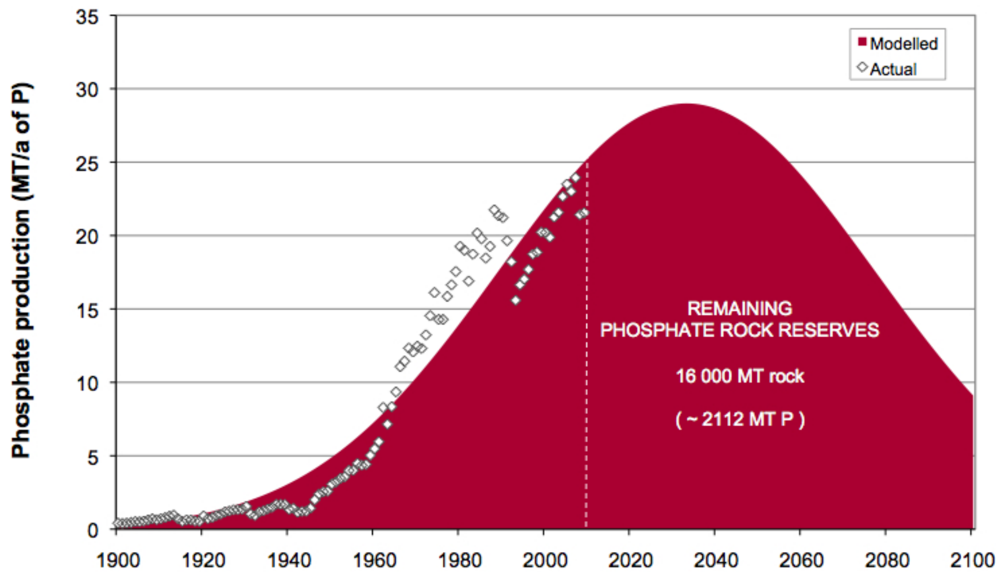
- increased energy and raw material consumption;
- increased production, processing and transport costs;
- increased generation of waste and pollution;
- further short-term price spikes;
- long-term trend of increased mineral phosphate prices;
- increased geopolitical tensions;
- reduced farmer access to fertilizer markets;
- reduced global crop yields; and
- increased global hunger.

4.2. Two Empirical Peak Phosphorus Studies—1988 Peak Year versus *2033 Peak Year*

While numerous scholars and visionaries have alluded to the finiteness of phosphate rock or the notion of future phosphorus scarcity over the past century [41,42], the term ‘peak phosphorus’ in this context only emerged in the scientific and public domains relatively recently. To date, all secondary references to peak phosphorus explicitly or implicitly refer to either the peak phosphorus analysis undertaken by Dery and Anderson [29], indicating a peak in phosphorus production occurred in 1988, or, the analysis undertaken by the authors in Figure 4 [1,30], indicating a peak phosphorus year of 2033. It is important to first clarify the key differences between these two studies, in order to discuss the relevance of peak phosphorus, and some common misunderstandings of the concept.

Whilst these two studies emerged around the same time, they were undertaken in isolation from one another. While the underlying concepts of these two analyses remain the same, they differ in two important ways. Dery and Anderson arrive at a peak year in the past (that is, 1988), because they do not use a constraining figure for total remaining reserves, citing a lack of reliability and distrust in the production of USGS data sets. Further, production data for the period up until 2006 is used, which results in a peak year of 1988.

Figure 4. Peak phosphorus curve indicating a peak in production by 2033, derived from US Geological Survey and industry data. Source: [1].



In our analysis, the published production data is fitted to a Gaussian distribution using a least squares method, in which the production data is fitted to the Gaussian and the total area under the curve is matched to the estimated total reserves. Therefore, when the published estimates of global phosphate rock reserves (that were available in 2008–2009) are used, this constrains the area under the curve and thus the solution for the peak year, and results in an estimate of the peak production of around 2033, as shown in Figure 4.

4.3. Limitations of Peak Phosphorus Analysis

Whilst there is a strong case for the validity of the peak phosphorus concept, and the implications for humanity of not preparing for a soft-landing approach in good time are serious, the analysis itself has several limitations. This section highlights some drawbacks of the peak phosphorus analysis. Firstly, determining the peak year is fraught with difficulties due to the unreliable estimates of the phosphate reserves. In fact, the peak is likely to be an extended and 'lumpy' plateau, rather than providing a specific year, in much the same way as the peak of oil production.

Whilst the application of Hubbert's curve can be informative for timely resource management (particularly critical for those resources like phosphorus which cannot be substituted), it is limited in the sense that it represents an ideal or single-variable situation. That is, it accounts for the time variable, however does not account for other variables such as external supply or demand-side factors. Some 'real-world' variables that can distort the perfect or ideal curve include:

1) Supply-side variables (can increase or decrease annual production):
   - Deliberate manipulation of annual production by major producing nations (for example, as in the case of OPEC fixing annual production of oil);
   - Geopolitical instability in a producing nation can disrupt and hence reduce annual output;
   - Raw material input constraints (such as the price of oil or sulfur) can reduce annual production;

2) Demand-side variables (can increase or decrease demand):
   - o Deliberate market distortions by major producing nations (such as China's export tariff on phosphate rock which further increased the price of phosphate rock thereby reducing short-term demand of the commodity);
   - o Global or regional economic booms or crashes (for example the 2008–2009 global economic downturn was thought to be responsible for a reduced demand in phosphate rock, while the collapse of the Soviet Union in 1989 led to a sudden drop in demand from a major phosphate consuming country);
   - o Local, regional or international policies directly or indirectly related to phosphate (such as environmental policies to use phosphorus more efficiently on the farm to reduce runoff and subsequent pollution); and
   - o Once critical soil phosphorus levels are reached in agricultural soils, only applying phosphorus to replace what is taken away in harvest is theoretically required, hence potentially reducing the demand for phosphate fertilizers.

These factors indicate that the exact timeline of the peak should be taken with a degree of caution (as with any predictive model to a greater or lesser extent). However (as noted in Section 3.4), there will always be a demand for phosphorus for food production for which a corresponding supply will be required.

4.4. Criticisms of Peak Phosphorus Analysis

Critics of the idea of peak production often argue that the market will take care of scarcity, that resource scarcity is relative, and one scarce resource can simply be replaced by another indefinitely, because as price rises, investment in new technology will always improve efficiency of extraction and use [42]. This is the basis of the market system–neoclassical economic theory—which functions for a narrowly defined system, but does not acknowledge the finite nature of non-renewable resources like phosphate rock (or oil). This means that the concepts of peak oil and peak phosphorus (which are based on the non-homogenous nature of non-renewable resources) are not supported by the adherents of the market system.

Other skeptics don't deny that phosphorus peaks will one day occur; rather, they dispute the *timeline* and insist a peak is more in the distant future [43]. For example: *"peak phosphate in my view will not be a peak phosphate on the supply side, which is the arguments being raised right now. In my view it will be a peak phosphate on demand, and that will be probably within the next 40 years"* [44].

However there is little analysis on which to base this, as most demand studies do not include the growing per capita demand for phosphorus-intensive meat and dairy products and the other changes described earlier. For example, Van Kauwenbergh's conclusion in the recent IFDC report that "*there is no indication there is going to be a "peak phosphorus" event within the next 20–25 years*" [45], is not based on any analysis of demand trends, let alone a peak phosphorus analysis [45] for a revised peak phosphorus analysis based on the IFDC reserve estimates.

5. Geopolitical, Environmental and Institutional Dimensions of Global Phosphorus Scarcity

Regardless of whether the timeline of peak phosphorus or the depletion of phosphate rock reserves is 30 or 300 years, there are a number of other pertinent challenges that in themselves contribute to phosphorus scarcity, including inequitable distribution of remaining reserves, environmental impacts and inefficient use.

5.1. Environmental Challenges

The processing of lower grade phosphate rock results in increasing concentrations of impurities (such as clays) or heavy metals like cadmium and uranium that are toxic to soils and humans and hence must be removed. Increasing energy (and other resources like sulfur) are therefore required to mine, process and extract the same nutrient value from phosphate rock while simultaneously generating more waste. Every ton of phosphate generates five tons of by-product phosphogypsum—which has higher levels of radiation that are currently considered as too high to allow re-use and hence must be stockpiled. Further, these environmental challenges are compounded by ongoing and increasing phosphorus pollution problems leading to eutrophication and dead zones around the world [46].

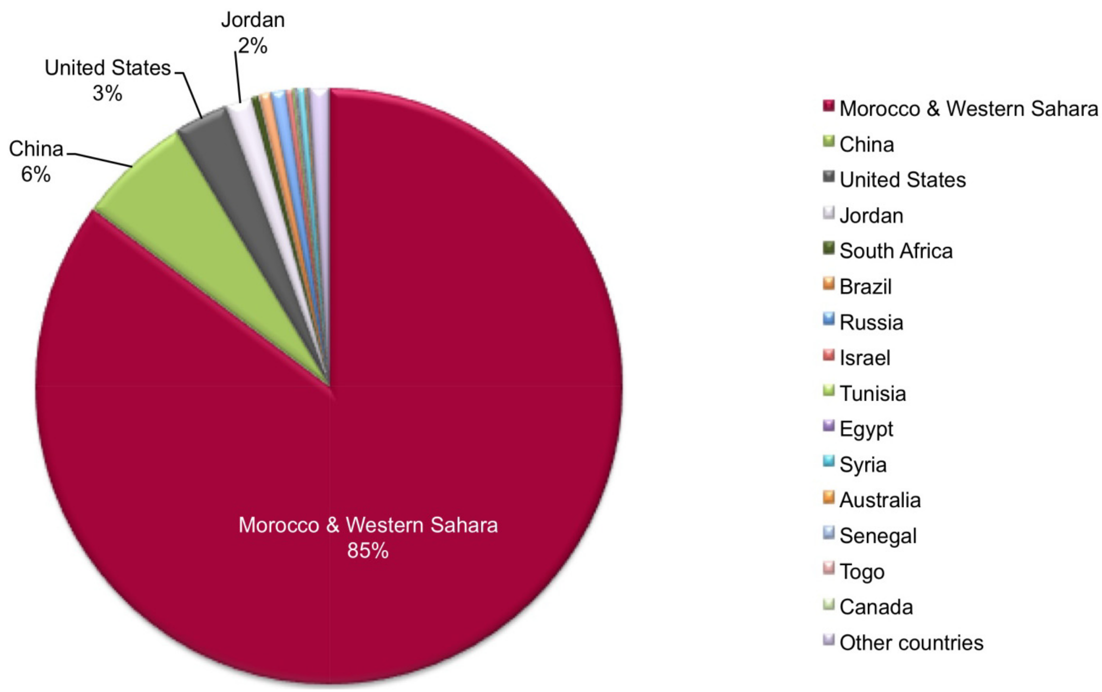
Exploration and mining (like most surface mining operations) disturbs the immediate natural landscape and ecosystems where the mine is located due to local land disturbances, air emissions, water contamination, noise and vibration. Such activities can have a relatively greater environmental impact in ecologically sensitive areas or highly populated areas (such as Florida). During the beneficiation (concentration) and the cleaning process some phosphate is lost when contaminants (such as iron phosphate) are removed and discharged to rivers or contained. Water pollution can also occur at this stage due to inappropriate management (such as breaking of tailings dams) [47].

However, the sustainability impacts of phosphate rock extend far beyond the mine. Processing and transporting phosphate fertilizers from the mine to the farm gate, which up to now have relied on cheap fossil fuels, involve an ever-increasing energy cost. For example, phosphate rock is one of the most highly traded commodities on the international market. Each year, around 30 million tons of phosphate rock and fertilizers are transported across the globe [48]. Also, phosphate fertilizer applied to Australian soils may have started as phosphate rock mined in Western Sahara or Morocco, shipped to the USA for processing into high analysis fertilizers and then shipped to Australia for distribution to inland farms. Typically, studies that aim to estimate the embodied energy of food do not take into account the embodied energy in the transport of fertilizers and their raw materials from the mine to processing to the farm gate in addition to the production and processing of the food itself.

5.2. Geopolitical Dimensions of Phosphorus Scarcity: Inequitable Distribution and Access

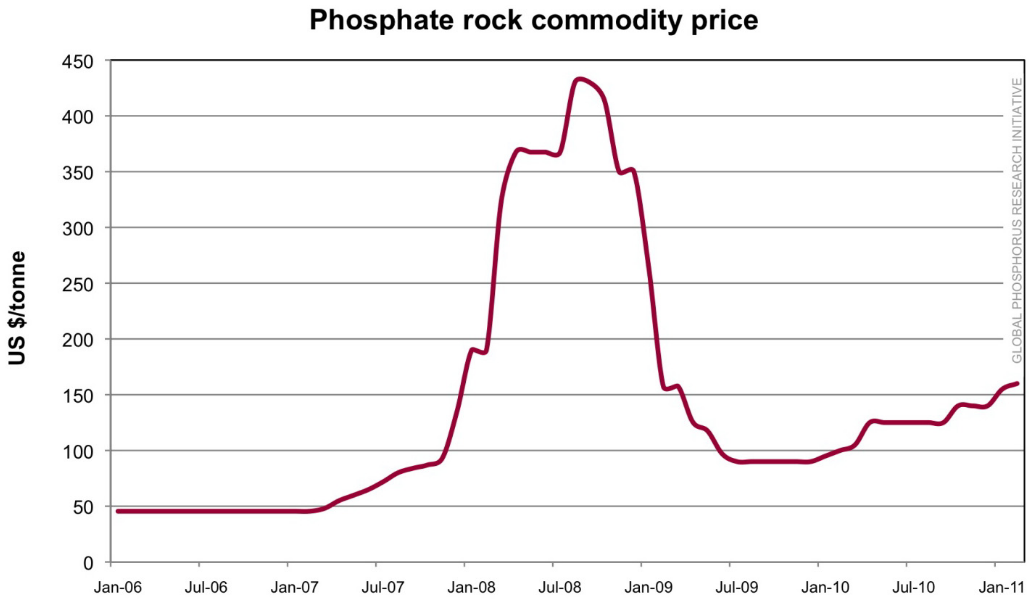
While all farmers need access to phosphorus, approximately 95% of the remaining reserves are controlled by five countries, including Morocco, China, USA, South Africa and Jordan (Figure 5). According to the recent IFDC and USGS studies [44,49], Morocco alone controls 85% of remaining reserves. Such an uneven distribution of one of the world's most important resources presents significant risks and warrants the attention of national leaders. Yet there are currently no international policies, guidelines or institutional arrangements in place to effectively govern phosphorus to ensure short and long-term accessibility and availability [8]. While China is one of the largest annual producers, it recently imposed a 135% export tariff on phosphate, effectively banning any exports in order to secure domestic supply. The USA, historically the world's largest producer, consumer, importer and exporter of phosphate rock and phosphate fertilizers, has approximately 25 years left of domestic reserves [41]. US companies import significant quantities of phosphate rock from Morocco to feed their phosphate fertilizer plants [50]. This is geopolitically sensitive as Morocco currently occupies Western Sahara and its massive phosphate rock reserves, contrary to international law. Trading with Morocco for Western Sahara's phosphate rock has been condemned by the UN and importing rock via Morocco has been boycotted by several Scandinavian firms [51,52].

Figure 5. Remaining global phosphate rock reserves as reported in 2010 by International Fertilizer Development Center (IFDC). Remaining reserves are highly geographically concentrated and are under the control of only a handful of countries. Data: [44].



In the long term, it is widely acknowledged that cheap fertilizers will become a thing of the past. As the remaining reserves decrease (below approximately 50%), capital costs can start to increase exponentially. This will have significant implications for farmers and food production systems. In the short term, an 800% spike in 2008 in the price of phosphate rock and other fertilizer commodities resulted from a combination of factors (including the price of oil, increased demand for fertilizers due to increasingly meat- and dairy-based diets, increased demand for non-food crops like biofuels and lack of short-term supply capacity to produce enough phosphate rock to meet demand). As a result of the price spike, farmers around the world held back on purchasing fertilizers, which partly caused the price to drop. The subsequent global financial crisis led to the sharp decline in demand and hence price. However the global financial crisis also pushed global food insecurity to an unprecedented level, with over one billion people hungry [53]. As of January 2011, the food price index has reached unprecedented levels, and phosphate rock prices are on the increase (Figure 6). There is general consensus that the quality and accessibility of the remaining phosphate reserves are decreasing, and costs are, and will continue to increase.

Figure 6. Phosphate rock price 2006–2011, indicating a spike in 2008, and gradual increase in 2010. Source: World Bank data 2006–2011.



5.3. Demand Mis-Management

While the apparent demand for phosphorus is increasing, the use of phosphorus in the entire food system from mine to field to fork is currently extremely inefficient. The global phosphorus flows analysis through the food production and consumption system in Cordell *et al.* [1] found that 80% of the phosphorus in rock never reaches the food consumed by humans—it is lost at all key stages. During mining and fertilizer production, as much as 30–40% of phosphorus can be lost during extraction and primary processing [38], while much of the phosphorus entering livestock and cropping systems ends up in manure and soils respectively. Losses in the 'post-harvest' food system (*i.e.*, between farm and fork) have been largely ignored until relatively recently. The globalized food commodity chain has resulted in more players, more processes, further distances and increased trade of commodities. Longer production chains in turn contribute to more food losses in the transport, production, storage and retail stages [54]. While Smil estimated global food losses in the commodity chain at approximately 50% [55], Lundqvist *et al.* [54] went on to estimate the embodied water in food losses. Further, recent studies have calculated the value of household food waste, which is in the order of £10 billion in Britain alone [56].

These multiple dimensions of phosphorus scarcity suggest that regardless of the exact year of peak phosphorus production, our local and global food systems are leaky and vulnerable to phosphorus scarcity and thus deliberate changes are required to create more sustainable and resilient systems.

6. Taking Stock: Consensus and Certainty Following Three Years of Rapid Change

There have been dramatic shifts in our collective understanding of, and the debate on, phosphorus scarcity since 2007. This section takes stock of where there is general consensus today, and which aspects are still largely contested [8]. There is a strong or reasonable level of consensus regarding:

- The essentiality of phosphorus food production and that there will always be a demand for phosphorus for the foreseeable future;
- That eutrophication of lakes and rivers is to a large degree a result of phosphorus run off and discharges from agriculture, sewage effluents and due to land use changes;
- That the global population (and hence mouths to feed) is increasing and expected to peak around 2050. Most of the new growth is likely to occur in peri-urban areas of developing countries;
- That Sub-Saharan African soils in particular are highly phosphorus deficient (both naturally and due to mismanagement or low application rates) and will require a significant boost in soil fertility in order to achieve high crop yields;
- That the demand for phosphorus is increasing, at least over the next few decades (associated with population, changing diet, and biofuels);
- That costs of mining and processing phosphate rock are increasing;
- That quality of phosphate ore is decreasing;
- That despite the uncertainty, more reliable data and analysis of phosphate rock is required;
- That phosphate rock is a finite resource and because large inefficiencies exist in the system, more sustainable use of phosphorus should involve increasing efficient use and recovery of phosphorus.

However there are still areas which are contested or uncertain, including:

- The peak phosphorus concept and timeline;
- The size of remaining phosphate rock reserves, in part due to the uncertainty regarding assumptions used for reporting what is ‘economically and technically feasible’ which varies from country to country;
- The actual long-term phosphorus demand (due to the latent demand in Africa, increasing meat-based diets, demand for biofuels and electric vehicle batteries);
- The extent to which new technology and the market can ‘fix’ the problem;
- The risk of exposure to elevated radiation levels from the decay of uranium in crushed rock is a risk associated with storage and use of phosphogypsum by-product;
- The amount of phosphorus potentially available for recovery contained in food waste, organic waste, phosphogypsum and other by-products during the mining, refining and fertilizer production processes;
- Implications and linkages to other resources, such as uranium, sulphur, potash;
- Sphere of responsibility regarding direct or indirect support for Morocco’s occupation of Western Sahara, and control of phosphate in that region;
- The quantity of organic (non-phosphate rock or guano) phosphorus sources used annually is very unclear due to lack of official or standardized monitoring and data collection. This includes the generation and reuse of manure, excreta, crop residues and other sources;

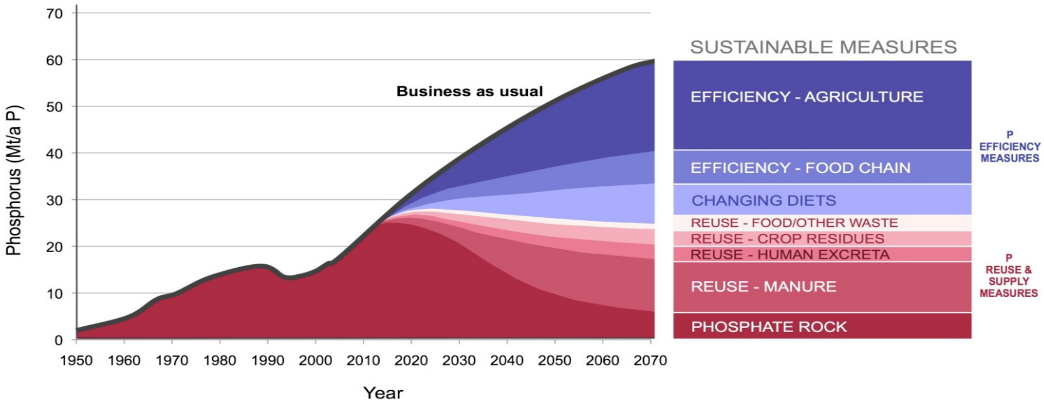
- The impacts of climate change on the demand and use of phosphorus resources, given changing rainfall patterns and increasing atmospheric CO_2 and the consequent impacts on agricultural production;
- The impacts of climate change policies on phosphorus use, for example, through changing land use and agricultural practices;
- Institutional roles and responsibilities and appropriate policy instruments (at the international and national level) for governing and coordinating the long-term management of phosphorus for food security.

Consensus is at least needed regarding the existence of the problem, the need to change the current system and the nature of the key challenges. However there will always be a degree of persistent uncertainty, that is, there will be issues we don't even know about, such as interlinked effects between phosphorus and other global drivers. Such uncertainties need to be managed as risks. This will require the application of the 'precautionary principle' of sustainable development and a response to the call from the resilience community to design more flexible systems able to adapt to new and unforeseen circumstances.

7. A Sustainable Future Pathway: Hard-Landing *versus* Soft-Landing Responses

Despite the presence of uncertainty and a lack of consensus about the timeline of phosphate reserves, it is highly likely that, unless we intentionally change the way we source and use phosphorus, we will end up in a 'hard-landing' situation. Not only will the gap between demand and supply widen, but the environmental and economic costs will continue to grow. For example, even if reserves are larger than previously thought, the geopolitical concentration of the reserves and increasing costs means importing nations and their food production systems are still highly vulnerable to fluctuations in availability and price volatility. Such countries will need to ensure all farmers have short- and long-term access to sufficient phosphorus to grow enough crops to feed a growing population. This is likely to require an integrated approach that includes (a) diversifying sources of phosphorus, by investing in renewable phosphorus fertilizers, and/or a high recovery rate of all sources of phosphorus from the food chain (crop residues, manure, food waste, human excreta); and (b) a large reduction in the demand for phosphorus brought about through measures ranging from increasing efficiency in agricultural use to reducing losses in the food chain and changing diets (Figure 7). In the sustainable scenario in Figure 7, the supply of phosphate rock is diverted earlier than the peak year, to (a) account for uncertainty if the actual peak is earlier, and (b) due to the substantial environmental and geopolitical issues associated with a dependence on one source.

Figure 7. A preferred scenario for meeting long-term global phosphorus demand: integrated demand management (efficiency) measures (blue) and supply-side (reuse) measures (red). Source: redrawn from [42].



Importantly, this indicates that to meet future food demand, sustainable phosphorus use initiatives will need to go beyond the current focus on efficiency in agriculture (on the demand side) and beyond recovery of phosphorus from excreta/wastewater (on the supply side). While demand management measures are typically the lowest-cost options to society, the exact situation will vary from country to country, hence region-specific phosphorus strategies should be developed. At the global scale, moving towards phosphorus security will result in outcomes such that [8]:

- the amounts of phosphorus (and related resources) that are wasted throughout the entire food production and consumption system are kept to a minimum;
- the use of phosphorus has no net negative impact, from its at-source effects or its downstream effects, on the environment, including water, land and biota;
- phosphorus fertilizers are produced, transported, used, recovered and managed in a way that minimizes life cycle energy consumption;
- sufficient phosphorus of appropriate quality is physically available both in the short term and longer term for farmers to utilize for fertilizers and the whole-of-society costs of producing, trading, using and recovering phosphorus are minimized;
- all the world's agricultural soils are sufficiently fertile to ensure high crop yields (with appropriate management) and sufficient fertilizers for food availability are secured ensuring global food security;
- all people have sufficient phosphorus intake for a healthy and balanced diet;
- geopolitical interests do not steer the sourcing, use or reuse of phosphorus for food production;
- there is equitable access to phosphorus sources and current and future generations are not compromised directly or indirectly by the sourcing, use or re-use of phosphorus for food production;
- there is independent, equitable and transparent governance of phosphorus resources for long-term food security.

8. Conclusions

The sudden emergence of the peak phosphorus and global phosphorus scarcity debate on the international arena has perhaps raised more questions than it has resolved. This paper has clarified the nature of many misunderstandings, particularly regarding what peak phosphorus is and is not, and through doing so, provides a more solid scientific basis from which sustainable pathways can be developed. While there is substantial uncertainty and lack of consensus regarding the size and longevity of remaining phosphate rock reserves, there is sufficient consensus between the scientific community, industry and others that the current situation is unsustainable with respect to the environmental impacts associated with the linear use (throughput) of phosphorus for food production (in particular eutrophication), inequitable access and geopolitics surrounding the unequal distribution of phosphate resources, the finite nature of phosphate rock and the inefficiency of phosphorus use throughout the current food production and consumption system.

In order to achieve a preferred 'soft-landing' outcome, an integrated and globally coordinated approach to managing phosphorus is required. This is likely to require substantial change in both the physical and institutional infrastructure surrounding the sourcing and supply of phosphorus for food production. There is no single solution to meeting future phosphorus demand and, while strategies need to respond to global issues, their design and implementation need to be context-specific. For example, for each region, country or catchment area, strategies could consider: what are the most cost-effective, energy efficient, equitable, environmentally compatible means of using and reusing phosphorus in a given food production & consumption system? Which actors need to be involved and what roles and responsibilities can they play to ensure long-term phosphorus security?

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