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Phosphorus vulnerability: A qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity

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ABSTRACT

The element phosphorus underpins the viability of global and national food systems, by ensuring soil fertility, maximising crop yields, supporting farmer livelihoods and ultimately nutritional security of the global population. The implications of global phosphorus scarcity therefore have serious potential consequences for future food security, yet these implications have not been be comprehensively or sufficiently assessed at the global or national scales. This paper offers a new integrated framework for assessing the vulnerability of national food systems to global phosphorus scarcity—the Phosphorus Vulnerability Assessment framework. Drawing on developments in assessing climate and water vulnerability, the framework identifies and integrates 26 phosphorus-related biophysical, technical, geopolitical, socio-economic and institutional factors that can lead to food system vulnerability. The theoretical framework allows analysis of context-specific food system by examining impact due to exposure, sensitivity and adaptive capacity. The framework will also ultimately provide guidance for food and agriculture policy-makers, phosphate producers and phosphorus end-users (primarily farmers and consumers) to take action to reduce their vulnerability to this new global challenge.

1. Introduction

There is little doubt today that the earth is experiencing unprecedented global changes due to human activity (Biermann et al., 2009; Folke and Rockström, 2009; Rockström et al., 2009; Solomon et al., 2007; Steffen et al., 2004; WWF, 2004). Phosphorus scarcity linked to food security is emerging as one of 21st Century's key global environmental challenges, yet it remains relatively understudied compared to other prominent challenge such as climate change, water scarcity, and nitrogen management.

In a world which is anticipated to be home to nine billion people by mid century, producing enough food and other vital resources is likely to be a substantial challenge for humanity. Phosphorus, together with nitrogen and potassium, is a plant nutrient, hence essential to crop growth and functioning. It is applied to agricultural soils in fertilizers to maintain high crop yields (Johnston, 2000). The use of such fertilizers has contributed to feeding billions of people over the past half-century (IFPRI, 2002). In contrast to nitrogen which can be fixed from the atmosphere by microbial-plant symbiosis, phosphorus must be physically added as fertilizer to supplement natural soil phosphorus. Phosphorus has no substitute in food production, hence securing the long-term availability and accessibility of phosphorus is crucial to global food security. While fertiliser demand is expected to increase in the long-term, the world's main source of phosphorus –phosphate rock – is a non-renewable resource and high quality reserves are becoming increasingly scarce and expensive (Childers et al., 2011; Cordell et al., 2009a; Neset et al., 2013; Smit et al., 2009).

Until recently, phosphorus has been predominantly framed as a pollutant, which is co-responsible for hundreds of eutrophied water bodies and aquatic 'dead zones' around the world. For example, the Planetary Boundaries framework (Rockström et al., 2009) identified phosphorus as one of nine planetary boundaries considered of global significance to humanity, yet the parameter used to determine the crucial limit is "quantity of P flowing into the oceans" (p. 473) linked to eutrophication. This does not take into account phosphorus depletion or phosphorus use relative to available stocks (as is the indicator for global freshwater use). In addition to defining the concept as a physical threshold, the impact of global phosphorus scarcity on food production could also be considered as a social threshold, in the context of global food security.

Importantly, phosphorus scarcity has at least five sustainability dimensions, which go beyond physical scarcity and also include

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geopolitical, institutional, economic and managerial scarcity (Cordell, 2010): (1) Physical scarcity refers to the physical availability of phosphorus, such as the lowering availability of the world's finite, high-quality phosphate rock reserves; (2) Economic scarcity refers to a lack of access to phosphorus, due to constraints in financial capacity, such as farmer purchasing power, or investments in new resources; (3) Managerial scarcity refers to improper management or maintenance of phosphorus, resulting in substantial system inefficiencies that limit the ability of available phosphorus to meet demand, such as phosphorus losses in the food production and consumption chain; (4) Institutional scarcity results from a lack of appropriate and effective global governance structures to ensure phosphorus supply will meet demand both in the short and long term, for all end users; and (5) Geopolitical scarcity refers to restricted availability or access to phosphorus resources due to political or geopolitical circumstances such as monopolies or oligopolies controlled by governments or corporations. The significance of these dimensions and examples are provided in latter parts of this paper, such as Table 1.

Since the price of phosphate rock spiked 800% in 2008, more attention has been placed on phosphorus as a scarce resource in addition to a pollutant. Global phosphorus scarcity is now receiving more mention in international discourses and reports on the food security challenge (e.g. Bekunda et al., 2011; European Phosphorus Platform, 2013; Pretty et al., 2010; Steffen et al., 2011; UN, 2012). In response to the increased awareness and debate over global phosphorus scarcity, recent quantitative studies have re-assessed the magnitude of the world's phosphate reserves which are currently estimated at 67,000 MT phosphate rock, up from 16,000 MT prior to 2010 (Jasinski, 2013, 2010; Van Kauwenbergh, 2010). The associated physical scarcity and longevity of these phosphate rock reserves has also been revised, ranging from 30 to 300 years (Cooper et al., 2011; Cordell and White, 2011; Fixen, 2009; Rustad, 2012; Scholz and Wellmer, 2013; Steen, 1998; Vaccari and Strigul, 2011; Van Kauwenbergh, 2010; Van Vuuren et al., 2010). Recent peak phosphorus analyses also vary, suggesting peak phosphorus could occur this century, possibly as soon as 2033, or as late as early 2100 (Cordell et al., 2011b, 2009a; Déry and Anderson, 2007; Mohr and Evans, 2013; Vaccari and Strigul, 2011). These studies vary widely due to differing methodologies, differing assumptions about demand growth as well as uncertainty and lack of transparency regarding national/industry estimates of phosphate rock reserves (Bekunda et al., 2011; Cordell and White, 2011).

New studies have also re-assessed the global and national inputs and outputs of phosphorus between and within sectors from mining to agriculture to food consumption (Cordell et al., 2012; Liu et al., 2008; e.g. Senthilkumar et al., 2012) and long-term future phosphorus scenarios for meeting food demand (e.g. Bouwman et al., 2009; Cordell et al., 2009b; Smit et al., 2009; Van Vuuren et al., 2010). While these studies are critical, they are limited in the sense that their analytical focus is predominantly the quantitative and physical dimension of scarcity (and to some extent economic and managerial scarcity). There is a need for robust qualitative scientific frameworks to compliment these quantitative analyses and address other crucial non-physical dimensions of phosphorus scarcity, particularly related to farmer fertilizer accessibility and geopolitical dimensions. Many of the world's 1 billion hungry people are poor smallholder farmers (and their families) who do not have sufficient purchasing power to access fertilizer markets (IAASTD, 2008). Increasing fertilizer prices resulting from increased scarcity would therefore exacerbate rather than alleviate the problem of inequitable access. Further, irrespective of farmer purchasing power, importing nations may be restricted in their access to phosphate rock due to geopolitical and market dynamics in producing countries. This geopolitical issue is starting to be addressed by researchers as well as international and national government bodies (e.g. HCSS, 2012; Mcgill, 2012; UN, 2012).

The purpose of this paper is therefore to introduce the concept of phosphorus vulnerability and present a qualitative scientific framework for assessing vulnerability to phosphorus scarcity. In this paper we ask, what would a national vulnerability assessment look like for the global challenge of phosphorus scarcity (learning from vulnerability framings in other scientific fields)? We present an initial conceptual framework to open up the discussion and consider how such a framework might be validated and further developed into a practical tool through country-level case studies with a strong focus on stakeholder participation. We draw on the recent body of phosphorus scarcity and sustainability research (including our own and other authors), resilience and earth system studies, climate change and other vulnerability literature and systems thinking.

2. Assessing vulnerability to global environmental challenges

The concept of vulnerability acknowledges that people and places are vulnerable to global environmental challenges such as climate change, water scarcity, food insecurity in very different ways. Luers (2005) defines the purpose of a vulnerability assessment to "identify people or places that are most susceptible to harm" (p. 215) and in turn "to help policy makers in defining where programmatic efforts to reduce vulnerability and facilitate adaptation should be made and in identifying what types of development paths might lead to greater vulnerability in the future" (Eakin and Luers, 2006, p. 384).

Vulnerability is a concept that has relevance in many traditions, perspectives and disciplines such as: ecology, public health, poverty and development, livelihoods security and famine, land use change, climate impacts and adaptation, and overarching fields such as sustainability science, global environmental change and risk and resilience (Adger, 2006; Füssel, 2007). Before discussing approaches to assessing vulnerability, we first highlight some of the key differences in understanding vulnerability. Vulnerability in some traditions is defined as a function of exposure and sensitivity of a system (Adger, 2006; Cutter et al., 2008), while other scholars specifically include the role of adaptive capacity into this equation (Füssel and Klein, 2006). In the literature on climate change vulnerability, several framings are relevant to a general environmental change context. Kelly and Adger (2000) distinguish the different definitions of vulnerability as either a 'starting-point' or 'end-point' approach. The end-point implies that vulnerability is a final state, resulting from a 'sequence of analyses' and finally identifies required adaptation actions (p. 327), while the starting-point approach describes vulnerability as a current state, generated by multiple factors.

In the climate vulnerability discourse, O'Brien et al. (2007) discusses two related interpretations of vulnerability: 'outcome vulnerability' and 'contextual vulnerability' which are linked to 'different discourses and framings of climate change'. Outcome vulnerability describes a linear development of exposure and effects, resulting in a measurable vulnerability. This reflects the natural science framing, implying that climate change is framed as a 'problem' derived by anthropogenic impact on the earth system. Contextual vulnerability considers climate changes to 'occur in the context of political, institutional, economic and social structures and changes, which interact dynamically with contextual conditions associated with a particular exposure unit' (O'Brien et al., 2007, p. 76). As such, contextual vulnerability is related to a human-security framing of climate change, which acknowledges