Phosphorus, food and 'messy' problems: A systemic inquiring into the management of a critical global resource

D. Cordell[1,2]

[1] Institute for Sustainable Futures
University of Technology, Sydney, AUSTRALIA

[2] Department of Water & Environmental Studies
Linköping University, SWEDEN
E-mail: Dana.Cordell@uts.edu.au

Abstract

This paper presents a process of systemic inquiry into the roles, relationships and perceptions in the management of phosphorus resources in the context of global food security. Phosphorus, like water, energy and nitrogen, is critical for food production. All modern food production and consumption systems are dependent on continual inputs of phosphate fertilizers derived from phosphate rock. Yet phosphate rock is a finite resource under the control of only a handful of countries – mainly China, Morocco and the US. Production of current global phosphate reserves could peak in 30 years, within decades of peak oil. Given this situation it is surprising that phosphorus is not considered a priority in the dominant discourses on global food security or global environmental change. Checkland's Soft Systems Methodology offers a framework to guide an inquiry or 'learning process' into the nature of the problem situation and system failure, incorporating results of an analysis of stakeholder interviews, a substance flows analysis and an institutional analysis. The soft systems inquiry reveals that not only is there no stakeholder consensus on the nature of the problem, there are no international institutional arrangements, much less an international organisation, responsible for monitoring and facilitating the long-term sustainability of phosphorus resources for food production. Further, without such an actor and associated institutional arrangements, there is no 'feedback loop' that can correct the system. Given the critical nature of phosphorus to all modern economies, this is a concerning finding and warrants further analysis, deliberation and enabling of change.

Keywords:

Phosphorus, global food security, soft systems methodology, stakeholder analysis, institutional analysis

INTRODUCTION: WHY SYSTEMS THINKING

Systems thinking is increasingly understood to be important in the sustainable management of our natural resources on a local, regional or global scale (eg. ESSP, online; Urban Water, 2006). However in reality, the institutional and physical structures that have been created over past decades - or even centuries – tend not to reflect this. This is evident from the nature of most centralised water and wastewater systems that have been the norm, through to the global food production and consumption system. Both systems are extremely resource and energy intensive and rarely make use of synergies between material flows (such as reuse of wastewater fractions rather than continually seeking new resources of water and nutrients) and adapting institutional arrangements to reflect these synergies.

This paper focuses on the sustainability of how we source and use phosphorus in the global food production and consumption system. While access to water and energy sources are now understood to be limiting factors to achieving global food security, the implications of future phosphate scarcity has not received explicit mention in key dialogues on global food security (for example, FAO, 2007; FAO, 2006; FAO, 2005; IFPRI, 2005; IFPRI, 2002; GECAFS, 2006; IAASTD, 2008; FAO, 2008). Figure 1 depicts four of the key current discourses on global food security, illustrating that phosphorus is missing from the picture and could be added.

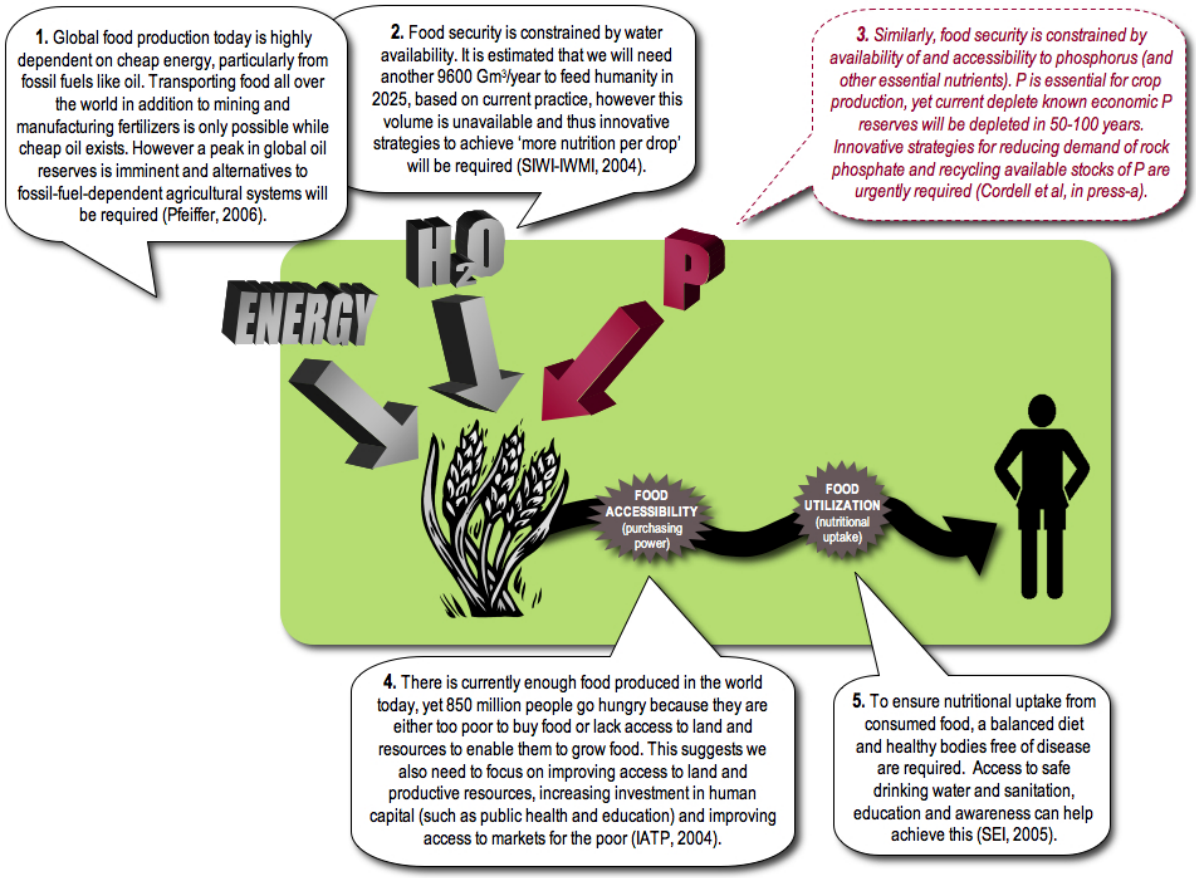

Figure 1: Dominant discourses on global food security: including accessibility to food, health, energy and water. Phosphorus scarcity currently does not appear in any dominant discourse, however in this paper it is argued here that is has been neglected, and should sit along side energy and water issues.

Phosphorus in the context of food production and the environment is most commonly framed as an environmental pollutant, that together with nitrogen, contributes to eutrophication and algal blooms worldwide (Mörth et al., 2007; World Resources Institute, 2008). Yet phosphorus is simultaneously a critical nutrient input in agriculture whose global reserves are being rapidly depleted. Rarely are phosphorus pollution and phosphate scarcity discussed in the same context.

The risks of not considering systemic links are exemplified by the recent increased global concern about oil scarcity and climate change leading to a rapid production boom of biofuel crops which not only compete with food production for prime fertile land, yet require profuse amounts of phosphorus fertilizers. This sudden increased demand for fertilizers worldwide has contributed to the seven-fold increase in the price of phosphate rock (IFA, 2008). In this sense, the peak oil problem is being shifted to a peak phosphorus problem, making the 'supra'-system unsustainable in the long-term. As succinctly put by Franzi Poldy "There are no sustainable parts of unsustainable wholes" (pers comm., 5th Feb 2008).

SOFT SYSTEMS METHODOLOGY AS A SYSTEMIC INQUIRY IN SUSTAINABLE FUTURES RESEARCH

The notions of *messy* problems (Ackoff, 1974), *wicked* problems (Rittel and Webber, 1973) and *metaproblems* (Cartwright, 1973) emerged from the group of systems approaches applied to planning and management fields. What messy, wicked and meta- problems all have in common are: a strong political and/or moral focus; no 'right or wrong' finding, but 'good or bad'; no stakeholder consensus and no obvious point at which a solution is reached (Abeysuriya, 2008; Rittel and Webber, 1973; Palmer et al., 2007). Further, they are often more concerned with problem understanding than problem solving (Palmer et al., 2007).

Soft Systems Methodology (SSM) is ideal to address these types of messy problems. SSM is explicitly a process of inquiry into a situation perceived as problematical. It has its origins in systems engineering, picking up where an approach that purely considers hard systems failed to address issues that were complex with a high social and political component, such as power dynamics (Checkland, 2001). SSM has evolved to become a dynamic, iterative process (Checkland, 2001), aptly described by Dick & Swepson (1994) as essentially 4 dialectics: Firstly, a dialectic between the problem situation (depicted as 'rich pictures') and a descriptive 'essence' (or root definition) of the situation; secondly, between this root definition and a conceptual model of the system developed by the researcher; thirdly the conceptual model is compared back to the original problem situation, with an intent to identify possible solutions to the problematic situation, resulting in a plan of action; Finally the dialectic between this plan of action and what is feasible and desirable in reality is assessed (Dick and Swepson, 1994). See figure 2.

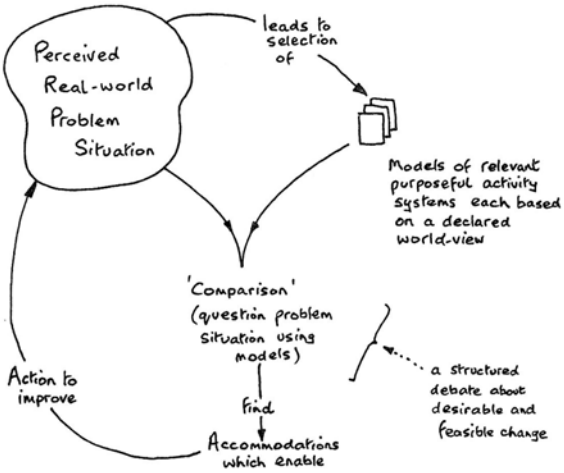

Figure 2: Checkland's depiction of the soft systems methodology as a dynamic and deliberative process (1999).

Although originally intended for organisational learning, SSM has been applied to a diverse range sustainable futures studies, including in the fields of international aid, transport, sanitation and water (Crawford, 2004; Zeibots, 2007; Abeysuriya, 2008; Attwater, 2007). SSM combines both a cultural and logical stream of inquiry. How the problem is perceived will determine the nature of the solutions (Abeysuriya, 2008; Cartwright, 1973). SSM is not an objective science, rather it is observer dependent, to acknowledge the "inescapable human involvement in knowledge production" (Brocklesby, 2007, p.158). SSM addresses this through explicit acknowledgement of the 'world view' (*Weltanschauung*), which informs development of the conceptual models (see section 4.2). Power and politics in relationships are also important elements of the systemic inquiry.

METHODOLOGY & ANALYTICAL FRAMEWORK

This systemic inquiry integrates findings from an analysis of stakeholder interivews (Cordell, *forthcoming*), a substance flows analysis (Cordell et al, *in press-a*) and institutional analyses (Cordell and Kerschner, *forthcoming*) that form a doctoral research project. SSM, and indeed general systemic inquiries are considered 'meta-disciplines' (Checkland and Poulter, 2006), rather than a method or tool exclusive to any specific discipline. Transdisciplinary sustainable futures research often requires both subjective and objective analyses, depending on the nature of the problem and questions of interest (Biermann, 2006; Bolin et al., 2000). SSM is one of few methodologies that allow both interpretivist and post-positivist approaches to be nested within the same framework. My research is inherently and purposefully transdisciplinary in nature. That is, the problem situation itself crosses disciplinary boundaries, from physical to social and institutional sciences and hence demands a transdisciplinary framework. This use of SSM focuses on the development and analysis of conceptual models, and, a broad comparison of the hard and soft systems pertaining to the problem area. The 'hard' (physical) and 'soft' (human activity) sub-system components are interlinked and embedded within a greater system (figure 3).

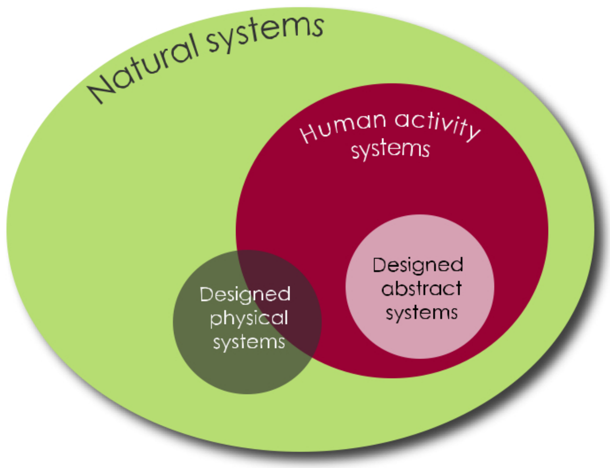

Figure 3: Checkland's systems classification, indicating embeddedness and basic relationships between natural, human activity, designed physical and designed abstract systems (source: redrawn from Zeibots (2007), in turn adapted from Checkland (1972)).

With attention to figure 3, the hard systems analysis in my doctoral research addresses the material flows of phosphorus within the *designed physical system* (the global food production and consumption system) and its interaction with the *natural system* (the lithosphere and hydrosphere). The soft systems analysis addresses the *human activity system* (in this case, the actors, rules, power structures and norms that govern the use of phosphorus in food production and consumption) and its relationships with both the designed physical system, natural system and its subsystems *designed abstract systems* (such as the market system).

Quantitative and qualitative data for these analyses have come from multiple sources, including the secondary data from the literature and primary data from stakeholder interviews (Cordell, *forthcoming*) and 'oral' information (that is, personal communications with experts). Data has been triangulated from these multiple sources.

ANALYSIS & FINDINGS

In accordance with Checkland's vision that SSM should be used as a 'learning process', the analysis presented below was by no means undertaken as a linear process, rather it was the result of an inductive and iterative inquiry.

Finding out

Typical of messy problems, there is no single agreed understanding of the problem situation. Multiple '*Weltanschauungen'* (worldviews) co-exist in an uncoordinated and at times conflicting manner. No actor is void of a *Weltanschauung*, including the researcher/practitioner using SSM as participant-observer. My declared worldview with respect to the problem situation is based on the principles of sustainable development, the laws of thermodynamics, livelihood security and the human right to food.

'Finding out' involves the construction of *rich pictures*, '*to capture the relationships in the situation of concern*' (Checkland, 2006, p.160). Multiple rich pictures were undertaken, drawing from the literature and in-depth, face-to-face interviews with international stakeholders related to key aspects of the phosphorus cycle through the global food production and consumption system. This included representatives from the Food and Agricultural Organisation (FAO), the International Fertilizer Industry Association (IFA), the World Health Organisation (WHO), United Nations Environment Program (UNEP), US Geological Survey (USGS) and the Ecological Sanitation Research Programme (EcoSanRes). The rich picture has been omitted from this paper due to stakeholder confidentiality. However key relationships depicted included: while all farmers need access to phosphorus fertilizers, only a handful of countries control the supply of phosphate rock (namely Morocco, China and US), with numerous distributors transporting rock and finished fertilizers across the globe to reach the world's farmers. There are many farmers operating with nutrient-deficient soil who are too poor to access fertilizer markets. Farmers who can access the market (and credit) can apply phosphorus fertilizers and achieve higher yields and hence increased potential profit. In this context, FAO's fertilizer actor works with farmers to help increase yields and farmer livelihoods through fertilizer use. Regarding types of phosphate fertilizers, the FAO actor focuses on phosphate rock sources (not organic sources), and does not foresee a phosphate rock supply problem in the future. This view regarding phosphate rock and availability is aligned with the fertilizer industry actor, the IFA, and indeed FAO and IFA collaborate on projects to increase usage of fertilizers particularly where yields are low and hunger is prevalent. While the WHO has recently published comprehensive guidelines on the safe reuse of human excreta (such as urine) as a fertilizer in agriculture (WHO, 2006), these guidelines are not being addressed by the FAO fertilizer strategy as the latter is based on phosphate rock. Additionally, at the time of the stakeholder interviews, there was no staff responsible for organic fertilizers at the FAO headquarters. While there is little concern about global phosphate scarcity at the international level in general, UNEP is actively concerned about the sustainability of the entire nitrogen cycle, and nitrogen runoff from agriculture (and sewage) causing algal blooms and dead zones.

Returning to the supply side, Western Saharan phosphate rock, which is controlled by Morocco, feeds much of the world. The US, previously the world's biggest producer, consumer, importer and exporter of phosphate rock, is running out of domestic reserves (approximately 25 years remaining (Stewart et al., 2005; Jasinski, 2008), and has long term contracts with Morocco, however it is claimed that "*extracting and trading with phosphates from Western Sahara are contrary to international law*" (WSRW, 2007). The fertilizer industry in general is a powerful and profitable actor because all modern agriculture currently depends on phosphate rock fertilizers, and there will always be more mouths to feed for the foreseeable future. Regarding food production, supermarkets are powerful food retailers, yet generate copious amounts of food waste (along with households and other sectors in the food industry).

A participant-observer in the problem situation

Between late 2007 to mid 2008, the problem situation (and the larger food/energy/water system – the 'supra-system' - it is embedded within) has undergone rapid changes. Consistent with Checkland's intention of SSM as a form of Action Research, I have been a participant observer in these changes, to the extent that I am both studying/observing the situation, and, have intentional and unintentional influences on the situation. Figure 4 depicts the key observed and participated changes that are significant to this research study. These interventions are indicated on a timeline, or more specifically a *lebenswelt* – "an interacting flux of events and ideas unfolding through time" (Vickers in Brocklesby, 2007, p.160).

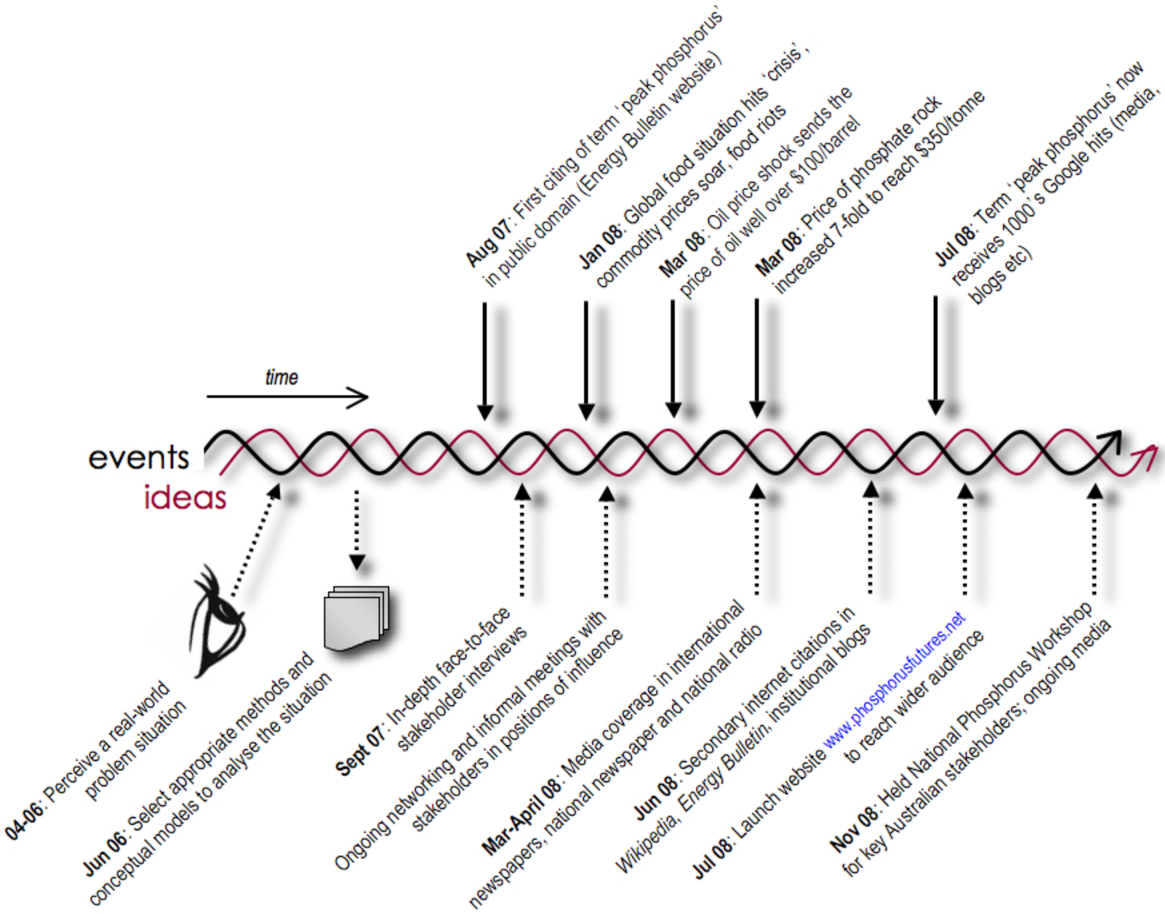

Figure 4: A participant observer in the perceived real-world dynamic problem situation between early 2006 and late 2008: key changes and events impacting on the situation under study. The events above the timeline are observed external events, while the events below are my intentional or unintentional interventions.

Ethics and system boundaries:

While defining a system boundary is not always a conscious decision, transparency regarding what is included and excluded is important as it can have serious implications for the analysis, and hence the findings. For example, many important socio-ecological models or conceptual frameworks of global environmental change and food systems (eg. MNP, 2006; GECAFS, 2006) do not include the phosphorus cycle, which means causal linkages of phosphate scarcity on global food security cannot be drawn, which in turn means no policy implications or funding of further research on the problem situation. This effectively perpetuates the overlooking of this significant phosphorus problem situation by policy makers, scientists and analysts.

In the analysis presented here, I have included the issue of Morocco's occupation of Western Sahara and its phosphate rock reserves, because a huge proportion of the world's agricultural fields are fertilized with rock from this region. There are two important dimensions here: 1. An ethical dimension of consumers and companies knowingly or unknowingly supporting an occupation that breaches human rights (WSRW, 2007; Corell, 2002); and, 2. the potential geopolitical consequences of a disruption of phosphate rock supply from the region. Other system boundary decisions relate to the exclusion of nitrogen and eutrophication from this study because their perceived problem situations are being addressed in other international academic and policy forums, such as the International Nitrogen Initiative (www.initrogen.org; UNEP, 2007) and the Helsinki Commission, HELCOM (www.helcom.fi), respectively.

Transformations and root definitions

While the finding out stage refers to the 'real world' situation, identifying 'transformations' and 'root definitions' are used to develop logical conceptual models pertaining to the activity at the heart of the situation. Transformations involve purposefully transforming a human activity input into an output (Checkland, 2001). In the case of the global phosphorus production and use system, this could be 'hungry people' transformed into 'sufficiently fed people'. Multiple transformations are possible and each is dependent on a worldview or *Weltanschauung*. Explicit acknowledgment of the *Weltanschauung* is essential and will influence the conceptual model and hence conclusions, as Rittel and Webber explain: "the choice of explanation determines the nature of the problem's resolution" (Rittel and Webber, 1973). This was reflected in findings from the stakeholder interviews (Cordell, forthcoming), where stakeholders perceived the problem situation and potential solutions very differently. For example, while some stakeholders thought there was no such thing as a phosphate supply problem at least for the next several hundred years and further that the market would always take care of demand, others felt a phosphate shortage was more imminent. Some of these *Weltanschauungen* and their transformations informing this analysis are provided in figure 5.

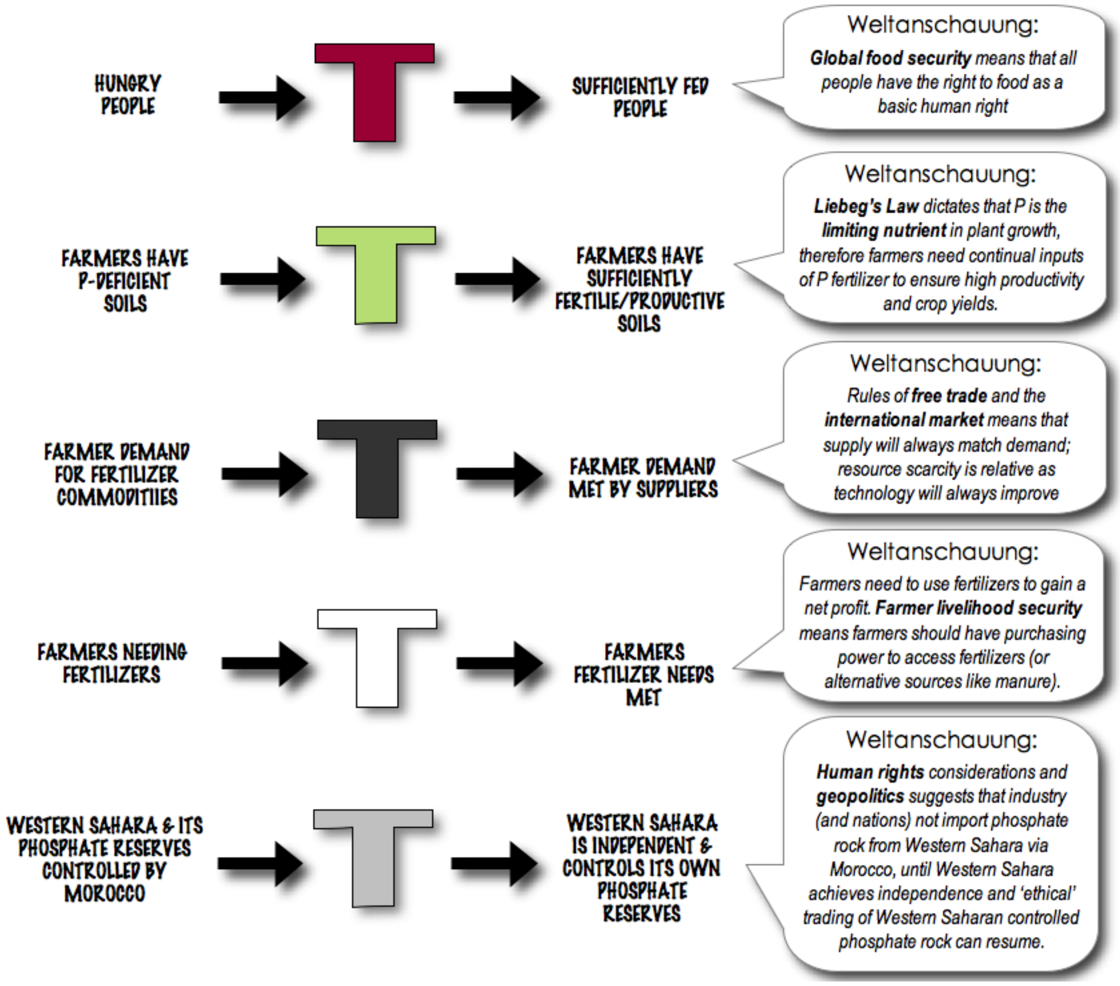

Figure 5: Multiple transformations (T) and associated Weltanschauungen (worldviews) by different stakeholders related to the global phosphorus production and use system, indicating that how the problem is perceived will determine the nature of the solutions.

The subsequent analysis attempts to distil and synthesize key elements of the transformations depicted in figure 5, with the primary transformation based on the *Weltanschauung* of global food security. The ideal or conceptual situation is analysed by applying the 'TWO CAGES' mnemonic (**T**ransformation, **W**eltanschauung, **O**wner, **C**ages, **A**ctors, **G**uardian, **E**nvironmental constraints, **S**ystem elements); for example, by asking who would be the 'Guardian' of the system if the system failed (Systemic Development Institute, 2005). This mnemonic is used to develop a root definition of the system of purposeful activity:

"A system to produce and use quality phosphorus fertilizer, by sustainable means, in order to meet the fertilizer needs of the world's farmers to feed the world population."

Based on this definition, the systems conceptual model in figure 6 was constructed. Checkland notes that when conceptual models are developed and compared to the 'real world' situation, we are seeking 'accommodations' rather than consensus (Checkland and Poulter, 2006).

Conceptual model building

The conceptual model defines key human activities linked by dependency arrows in the purposeful activity. In this case, the system involves: phosphorus suppliers obtaining raw phosphorus material (subject to given constraints of food demand, ethical considerations, cost, potential for recovery from used sources, environmental concerns); which is then converted to quality phosphate fertilizers and sold/distributed to farmers for use (subject to farmer purchasing power). Food producers convert the inputs to food, which is then sold/distributed to hungry people (subject to constraints of purchasing power).

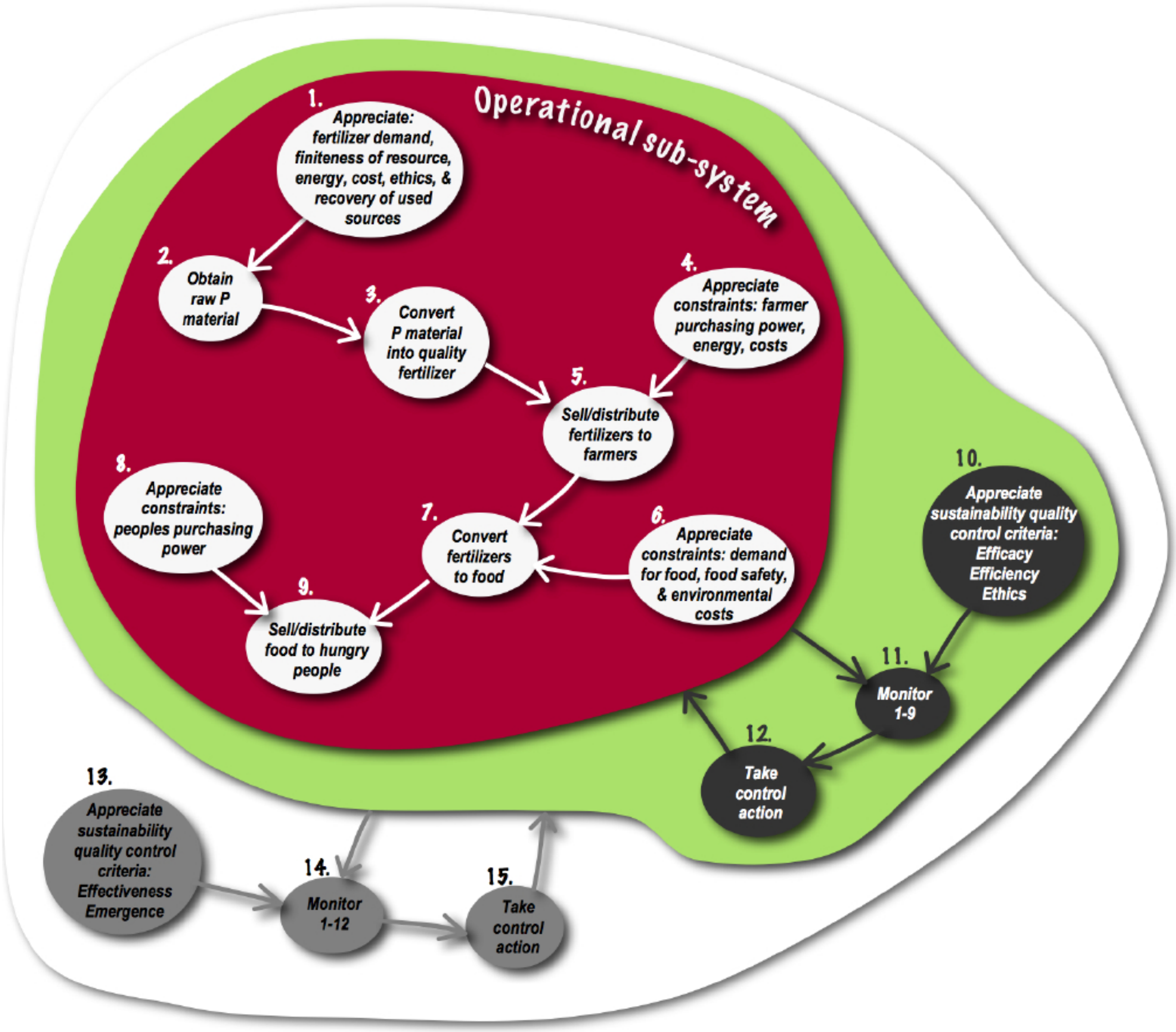

Figure 6: Conceptual model of the system, including operational activities sub-system, monitoring and control. This is based on the purposeful activity defined as "A system to produce and use quality phosphorus fertilizer, by sustainable means, in order to meet the fertilizer needs of the world's farmers to feed the world population".

Systems theory dictates that any complex system must have the capacity to self organise, hence contain elements of monitoring, feedback and control (Systemic Development Institute, 2008). SSM (Checkland, 1999) articulates this by imposed criteria of at minimum 3 E's: 1. Effectiveness ("*is this the right thing to be doing*?"), 2. Efficacy ("*does the means work?*") and 3. Efficiency ("*is there a minimum use of resources?*"). I have added a 4th and 5th E: 4. Ethics (*Are the whole system and sub-system components ethical?*), and a 5. *Emergence* (*Does the system exhibit properties of emergence (eg. synergies) when considered in the context of its' supra-system?*). These 4th and 5th E's are otherwise not explicit in Soft Systems application, yet are important criteria in this situation (given the high human rights dimension of food security, farmer livelihoods and the geopolitical dimensions of resource trade).

In Figure 6, the sub-system of operational activity (1-9), is subject to sustainability quality control criteria Efficacy, Efficiency and Ethics, which ensures: quality phosphorus fertilizers are available and accessible to farmers in the longer-term and hungry peoples' needs are met, use of resources and environmental damage are minimised and raw phosphorus material comes from ethical sources. These criteria are used by a 'Guardian' to track the performance of the system and take action if the system is not meeting the criteria. This greater system (activities 1-12) is then monitored against the sustainability quality control criteria Effectiveness and Emergence, which are viewed at a higher system level than the other three E's.

Comparing the conceptual model to real world

Once the conceptual model is constructed, a comparison of the conceptual system model (figure 6) with the 'real world' situation takes place. This comparison reveals several key insights into the current situation and possible areas for future changes or accommodations:

a) **Monitoring and control**. Perhaps the most striking finding is that in the current system, there is no 'guardian' in the real world situation. That is, there is currently no intentional and coordinated monitoring sub-system that provides meaningful and timely feedback to the operational activities. The feedback loop that does exist in the real world is the market signal. The price of phosphate rock has now risen 700% in 14 months, contributing to the current global food crisis and forcing farmers to either not fertilize or risk debts.

b) **Sustainability quality control criteria**. Secondly, there are no comprehensive sustainability quality control criteria (similar to the 5Es) in existence or associated feedback loops. Such negative feedback loops are essential for any operating system to function efficiently and effectively. As noted by Brown: "Any system in a state of positive feedback will destroy itself unless a limit is placed on the flow of energy through that system" (Brown, 2003). Applying the 5E's in the real world situation, uncovers (table 1):

Table 1: Assessing the current 'real world' situation against '5E' Sustainability criteria: Effectiveness, Efficacy, Efficiency, Ethics, Emergence.

1. Effectiveness: *Is providing farmers with phosphate fertilizers the right thing to be doing?*	All living organisms – including plants and animals – require phosphorus to grow. Natural phosphorus-soil levels are typically too low to achieve high crop yields required to feed a growing world population. Therefore for the foreseeable future some kind of external phosphorus fertilizer inputs (whether inorganic or organic) is required. However, producing and using phosphorus fertilizers is not the only way to achieve high crop yields to meet global food demand. Another important consideration is better managing soil characteristics (eg. carbon, pH, water) to allow greater uptake of phosphorus fertilizer by crops. Further, consumer preferences towards less meat and dairy can reduce the demand for phosphorus fertilizers (Cordell *et al, in press-b*).
2. Efficacy: *Does mining and trade of phosphate rock fertilizers 'work'?*	For the medium-term, mining and trade of phosphate rock generally 'works' for those farmers with purchasing power, though as a finite resource, costs will increase and a point will eventually reached (like Peak phosphorus) in the longer term, when the system no longer 'works'. The current (short-term) system does not 'work' in the sense that all farmers currently do not have access to phosphate rock and demand is greater than supply, due to the lag time of years in commissioning new phosphate rock mines (Cordell *et al, in press-a*).
3. Efficiency: *Is there a minimum use of resources such as energy and phosphate rock?*	Currently, there are significant inefficiencies in the system. 80% of the phosphorus we mine for fertilizers never reaches our dinner plate (Cordell et al, *in press*). There are phosphorus losses at almost all stages of the food production and consumption system: during production, global distribution, application, food processing, livestock production, and food preparation. These stages in the process also involve significant energy consumption.
4. Ethics: *Are the operational activities undertaken ethically?*	Some argue today that the use of phosphate rock as an absolute is unethical, for example (a) in relation to inter-generational equity, because it is depleting a non-renewable resource that will not be available to future generations, or (b) due to the radioactivity associated with phosphate rock. Others argue that using phosphate rock is currently unethical if sourced from Western Sahara because it is supporting an occupation by Morocco (Cordell et al, in press-a).
5. Emergence: *Does the system exhibit properties of emergence (eg. synergies) when considered in the context of its' supra-system, the food, water, sanitation, energy system?*	The current system does not exhibit significant synergies, while great potential exists. For example, synergies between institutional and material arrangements (eg. the sanitizers doubling as entrepreneurs supplying fertilizers also reduces the burden of the environmental managers responsible for river/water health and continuous pollution loads like sewage).

c) **Environmental Constraints**. The perceived environmental constraints rely on in part which *Weltanschauung* is acknowledged by which actor. For example, because the dominant *Weltanschauung* of the current phosphorus suppliers (Morocco, US, China and the fertilizer industry in general) that currently drives the system is perfect substitutability and technological optimism (neoclassical economics), then there are no perceived physical constraints to phosphorus resources. However if a different *Weltanschauung* is perceived, then the plausibility of Peak phosphorus means an environmental constraint is that production of high quality, easily accessible resource will eventually have to peak, followed by a steep decline and growing gap between supply and demand. Further environmental constraints would include that agricultural crops require continual addition of external fertilizer inputs; and, that excess and/or inappropriate application of phosphorus fertilizer can lead to eutrophied waterways.

d) **Beneficiaries and Victims**: Current beneficiaries are the phosphorus suppliers/distributors (the phosphate rock fertilizer industry) and farmers and hungry people who have purchasing power. Current victims are poor farmers and poor hungry people, Western Sahara, and the environment suffering from intermittent algal blooms. However in the ideal system, the beneficiaries are all farmers (increased productivity means increased profit (or no deficit); all households, because they have enough food to eat; new phosphorus suppliers (entrepreneurs obtaining phosphorus from renewable sources); Western Sahara if it achieves independence and the right to its own phosphate rock reserves; the environment if constraints to reduce/divert phosphorus flows to receiving water bodies are imposed. Current powerful phosphorus suppliers and their shareholders may lose some degree of power and profits to new players, if phosphorus production is distributed more evenly.

In the current system there is an obvious imbalance not just between human actors, but also between non-human entities. Figure 7 highlights a polarisation between the most powerful and least powerful actors or entities. An institutional and stakeholder analysis (reported in Cordell and Kerschner, forthcoming) revealed that the dominant institution and discourse governing global phosphorus resources is the international market. This is supported by neoclassical economics' rules of 'technological optimism' and 'relative scarcity' in relation to resource scarcity. Whilst alternative discourses exist (such as organic farming, the laws of thermodynamics), they are not upheld by the dominant stakeholders, hence do not play out in the governance of phosphorus.

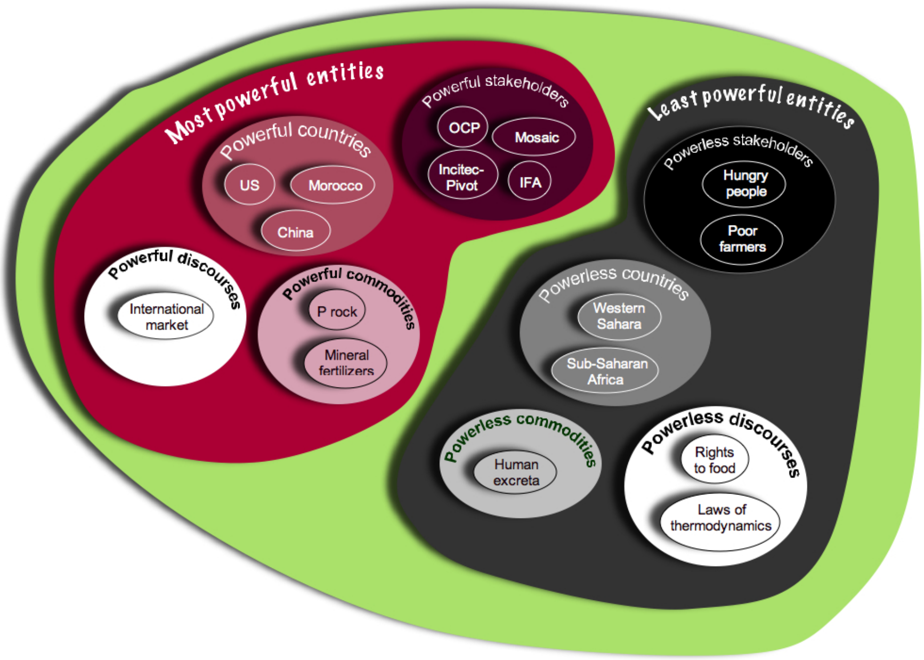

Figure 7: Powerful and least powerful entities in the system of meeting phosphorus fertilizer needs for global food security. This includes both human and non-human actors: countries, discourses, commodities, and stakeholders.

In contrast to the most powerful producing countries (Morocco, China, US), least powerful countries include Sub-Saharan Africa where phosphate deficient soils and food insecurity are prevalent, and Western Sahara for reasons outlined earlier. The most powerful commodity, in terms of phosphate fertilizers, is mineral fertilizers derived from phosphate rock, although phosphorus can be sourced from multiple organic and inorganic sources. Least powerful commodities include those derived from human excreta, such as urine as a liquid fertilizer.

Whilst human excreta presents a significant source of plant available P, a 'urine blindness' (Drangert, 1998) and general aversion to human excreta prevents policy makers and professionals from seeing the value in this resource.

The 'hard' system analysis

A quantitative analysis of phosphorus flows through the global food production and consumption system (presented in Cordell et al, in press-a) facilitates the identification of possible improvements to the 'hard' or physical aspects of the problem situation, The analysis uses the Substance Flows Analysis tool from Industrial Ecology (Brunner and Rechberge, 2004; Graedel, 1996), to track the major flows of phosphorus (in million tonnes P/yr) from mine to field to food processing, food consumption and excretion. The analysis indicates how much phosphorus the agriculture sector applies as fertilizer each year, how much actually ends up in the food we eat, where the major losses in the system are, how much phosphorus is used for animal feed and so on. For example, every year, the global population excretes around 3 million tonnes of phosphorus in urine and faeces, most of this ending up in water bodies. This hard systems analysis identifies opportunities for simultaneously and synergistically minimising phosphorus losses from the farm to reduce algal blooms in receiving waterways and addressing the phosphorus scarcity issue by recirculating renewable phosphorus sources, like manure, human excreta and food residues (Cordell *et al, in press-a).*

Linking the hard and soft systems

Checkland suggests that SSM is put to best use when applied as an "intellectual adventure" (Checkland and Poulter, 2006, p.160). The hard (physical) and soft (human activity, institutional) systems are therefore also compared to yield new insights. The comparison exposes further possible causes for the current system failure, most notably, a 'lack of fit' (Young, 2005). Young here refers to the mismatch between a biogeochemical cycle and the institutional arrangements governing it. This lack of fit is evident in both spatial and temporal terms. Spatially, while phosphorus flows through the food we eat and through our bodies to our excreta, there is little institutional linkage between the food and sanitation actors. Related to this, there is a noticeable fragmentation between the different sectors that phosphorus flows through in the global food production and consumption system (figure 8). There is little or no agreement on how phosphorus is conceptualised in society, rather, there are multiple perceptions, some of which are conflicting, consistent with Biermann et al's notion of '*conflictive fragmentation'* of institutional architecture (Biermann, 2007, p.4).

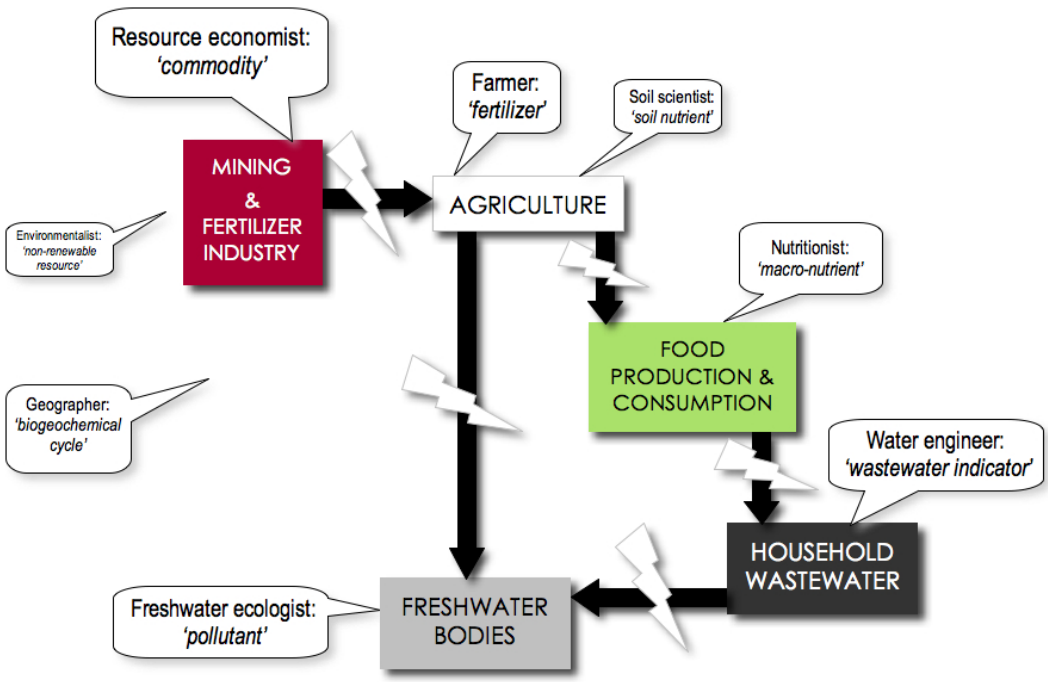

Figure 8: Institutional fragmentation of the global phosphorus cycle through the food production and consumption system. The size of the speech bubbles are indicative of the relative power or popularity currently attributed to that perception of phosphorus.

Further, complex systems logic suggests that if the whole is greater than the sum of the parts, it follows that fragmented system components have the potential to be undervalued. Indeed, phosphate scarcity or sustainability is not currently perceived as a priority in any of the sectors in figure 8 and no other institutional net captures it. This was indeed found to be the case in a related study of the human activity system around the collection and reuse of human urine in Australia, where such institutional fragmentation lead to the concept of reusing human urine as a 'homeless paradigm' where the full sustainability benefits could never be truly realised in the institutionally fragmented system (Cordell, 2006).

As noted when comparing the conceptual model with the real world, in the absence of an intentional and coordinated institutional regime, phosphorus resources are by default governed by the forces of the international market and its actors. The premises of the market system in the market context is that phosphate scarcity is only relative, and that new sources will always be available as prices rise and technology improves. However, this form of 'regime' is only sufficient to govern part of the system (such as efficiency of trade), and ignores many fundamental relationships and functions of the whole system, most notably the finiteness of phosphate rock and equitable distribution among consumers. Young warns that "faulty models or misleading discourses can go far toward producing mismatches between ecosystems and the attributes of regimes humans create to govern their interactions with these systems" (Young, 2005, p.17).

Figure 8 also illustrates how these different perceptions are not of equal power or popularity in the current system. For example, the resource economist's perception of phosphorus a tradable 'commodity' is perhaps the strongest voice in the system (Cordell and Kerschner, forthcoming).

In a temporal sense, the typical rate of change of global biophysical systems (here the phosphorus cycle) is too slow to be picked up by the current dominant institutional arrangements – the international market. There is a temporal mismatch of at least an order of magnitude, for example, current global phosphate reserves might be depleted in the next 50-100 years, which is very significant for humanity, yet the market system ignores this as it only operates on timelines of 5-10 years at most. This change in the global phosphorus cycle is also below the radar or early warning system of almost any political decision makers as their timelines are similarly short-term. The consequences of this are serious, as the system will eventually reach a tipping point (a peak production in the case of phosphorus, estimated at around 2033 in Cordell *et al, in press-a*), where the biophysical change is too fast for the 'sluggish' institutional change to keep up in a timely manner. Young notes that institutional arrangements "often change or evolve at a much slower pace [than biophysical and technological changes]; major adjustments in many…resource regimes can take years to decades" (2005, p.22). In the case of phosphorus, significant changes in both institutional and physical infrastructure will be required that could take decades to implement.

CONCLUSIONS

Through a structured systemic inquiry, this analysis has explored the problem situation related to the sustainability of global phosphate resources for food security. The analysis finds there is no 'guardian' of the human active system at the heart of this situation, coordinating the monitoring of phosphorus in this context and highlights the way the human activity system around the phosphorus cycle has been fragmented. There are also significant power imbalances in the system under inquiry, not only between human actors, but also between discourses and between commodities. In order to ensure the long-term, equitable and sustainable governance of phosphate fertilizers for the world's farmers to in turn ensure the global population can be fed, these institutional and geopolitical issues will need to be addressed and adapted accordingly in addition to addressing physical dimensions of sustainable phosphate fertilizer provision and management.

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