The Story of Phosphorus

Sustainability implications of global phosphorus scarcity for food security

PhD thesis

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This thesis is the product of a *cotutelle* agreement (collaborative doctoral degree) between the following two institutions:

Institute for Sustainable Futures, University of Technology, Sydney
(PhD in Sustainable Futures)

and

Department of Water and Environmental Studies, Linköping University
(PhD in Water and Environmental Studies)

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree and nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and in the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student

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When I told people I was undertaking a joint PhD literally between Australia and Sweden, they tended to visualize an exotic life of a young researcher networking the globe and chasing endless summers between Sydney's sunny beaches and Sweden's idyllic forests bursting with wild blueberries and *kantareller* mushrooms. While that image was relatively true, there was the less exotic side of physically shifting an office worth of literature and ideas back and forth across the globe; of never fitting into bureaucratic boxes of the universities, immigration board or insurance companies; of continually packing and unpacking apartments, of missing the births, weddings and birthdays of friends and family; not to mention the guilt of clocking up thousands of CO_2 miles, all in the name of 'sustainability' research.

Finding the motivation to work day and night for 3½ years was rarely a challenge in this doctoral journey. The topic was enthralling and the research exhilarating to me at (almost) all times. Even frequent face-to-face supervisor meetings across time zones that differed by eight hours were quite straightforward thanks to *skype* and *iCHAT* and inbuilt laptop cameras. The real challenges were: firstly, commencing research on a problem situation that many scientists and policy-makers dismissed because they believed 'the market would take care of it'; secondly, taking to the scientific investigation a non-conventional transdisciplinary approach that responded to the changing situation rather than adhering to a single, traditional disciplinary boundary; and finally, navigating a PhD between not just two countries, but two very different university institutions with different values, structures and approaches.

What made this challenging PhD possible and indeed, what made this thesis what it is, were the numerous mentors I gained as I travelled across the globe. Mentors come in all shapes and sizes, from supervisors and colleagues, to friends and family to strangers sitting next to you on long-haul flights from Sydney to Stockholm. This web of mentors knew what tricky or reflective questions to ask, and supported my transdisciplinary approach and research when others were dismissing it as unconventional. Through my doctoral travels, there's been an unbelievable growing network of mentors, friends, colleagues and administrators who have supported my research in many many ways (hence the length of this 'Acknowledgements' section).

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PAPERS

This thesis is based on the following five papers, which will be referred to in the text by their Roman numerals:

Paper I:

Cordell, D., Drangert, J.-O., and White, S., (2009), *The story of phosphorus: Global food security and food for thought*. **Global Environmental Change**, 2009. 19(2009) p. 292-305.

Paper II:

Cordell, D. (2008), *Phosphorus, food and 'messy' problems: A systemic inquiry into the management of a critical global resource*, ANZSYS 2008, Edith Cowan University, December 2008 in Proceedings of the 14th **ANZSYS Australia New Zealand Systems Society Conference**, ed David Cook, SECAU - Security Research Centre, Edith Cowan University, Perth, pp. 1-15. ISBN 978-0-7298-0668-8. (Reprinted with permission from Edith Cowan University and ANZSYS 2008 Conference Committee).

Paper III:

Cordell, D. (submitted), *Phosphorus: A nutrient with no home – multiple stakeholder perspectives on a critical global resource for food security* (Submitted for publication).

Paper IV:

Cordell, D., Neset, T. S. S., Drangert, J.-O. & White, S. (2009), *Preferred future phosphorus scenarios: A framework for meeting long-term phosphorus needs for global food demand*, International Conference on Nutrient Recovery from Wastewater Streams, Vancouver, 2009. Edited by Don Mavinic, Ken Ashley and Fred Koch. ISBN: 9781843392323. Published by **IWA Publishing**, London, UK. (p.23-44 reprinted with permission from the copyright holders, IWA Publishing).

Paper V

Cordell, D. & White, S. (submitted), *The Australian story of phosphorus: Implications of global phosphate scarcity for a nation built on the sheep's back* (Submitted for publication).

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LIST OF ABBREVIATIONS

CEEP	*Centre Européen d'Etudes sur les Polyphosphates (representing the European industrial/cleaning sector of the phosphate industry)*
CGIAR	*Consultative Group on International Agricultural Research*
CSIRO	*Commonwealth Scientific and Industrial Research Organization (Australia)*
CST	*Critical systems thinking*
CRU	*British Sulphur Consultants*
DAP	*Diammonium phosphate*
ESG	*Earth System Governance project*
ESSP	*Earth System Science Partnership*
FAO	*Food and Agricultural Organization of the United Nations*
FAOSTATS	*Online statistical database of the FAO*
FIFA	*Fertilizer Industry Federation of Australia*
GEC	*Global environmental change*
GECAFS	*Global Environmental Change and Food Systems program*
GPRI	*Global Phosphorus Research Initiative*
IAASTD	*International Assessment of Agricultural Knowledge, Science and Technology for Development*
IDGEC	*Institutional Dimensions of Global Environmental Change*
IFA	*International Fertilizer Industry Association*
IFADATA	*Online statistical database of the IFA*
iFOAM	*International Federation of Organic Agriculture Movements*
IFPRI	*International Food Policy Research Institute*
IMPHOS	*The World Phosphate Institute*
K	*Potassium*
MAP[1]	*Monoammonium phosphate*
MDG	*Millennium Development Goals*
MT	*Million metric tonnes*
N	*Nitrogen*
OCP	*Office Cherifien de Phosphate (Morocco's phosphate company)*
P	*Phosphorus*
SEI	*Stockholm Environment Institute*
SFA	*Substance Flows Analysis*
SSM	*Soft systems methodology*
TSP	*Triple Superphosphate*
UDHR	*Universal Declaration on Human Rights*
UN	*United Nations*
USGS	*US Geological Survey*
WHO	*World Health Organization of the United Nations*
WTO	*World Trade Organization*

[1] Struvite is also referred to as MAP (magnesium-ammonium-phosphate), however to avoid ambiguity, the common name struvite has been used.

ABSTRACT

The story of phosphorus began with the search for the philosopher's stone, and centuries later the critical role of phosphorus in soil fertility and crop growth was highlighted. Eventually, phosphorus was implicated in the global environmental challenge of eutrophication. Now, we are on the brink of yet another emerging chapter in the story: global phosphorus scarcity linked to food security. Through a transdisciplinary and systemic inquiry, this thesis has analyzed, reconceptualized and synthesized the physical and institutional dimensions of global phosphorus scarcity in the context of food security, leading to a new framing, 'phosphorus security' to guide future work towards a more sustainable and food secure pathway.

In a world which will be home to nine billion people by the middle of this century, producing enough food and other vital resources is likely to be a substantial challenge for humanity. Phosphorus, together with nitrogen and potassium, is an essential plant nutrient. It is applied to agricultural soils in fertilizers to maintain high crop yields. Phosphorus has no substitute in food production. Therefore, securing the long-term availability and accessibility of phosphorus is crucial to global food security. However the major source of phosphorus today, phosphate rock, is a non-renewable resource and high quality reserves are becoming increasingly scarce. This thesis estimates peak phosphorus to occur before 2035, after which demand will exceed supply. Phosphorus scarcity is defined by more than just *physical* scarcity of phosphate rock and this thesis develops five important dimensions. For example, there is a scarcity of *management* of phosphorus throughout the entire food production and consumption system: the global phosphorus flows analysis found that only 20% of phosphorus in phosphate rock mined for food production actually reaches the food consumed by the global population due to substantial inefficiencies and losses from mine to field to fork. There is also an *economic* scarcity, where for example, while all the world's farmers need access to sufficient fertilizers, only those with sufficient purchasing power can access fertilizer markets. *Institutional* scarcity, such as the lack of governance structures at the international level that explicitly aim to ensure long-term availability of and access to global phosphorus resources for food production that has led to ineffective and fragmented governance of phosphorus, including a lack of: overall coordination, monitoring and feedback, clear roles and responsibilities, long-term planning and equitable distribution. Finally, *geopolitical* scarcity arising from 90% of the world's remaining high-grade phosphate rock reserves being controlled by just five countries (a majority of which are subject to geopolitical tensions) can limit the availability of phosphorus on the market and raises serious ethical questions.

The long-term future scenarios presented in this thesis indicate that meeting future global food demand will likely require a substantial reduction in the global demand for phosphorus through not only improved efficient use of phosphorus in agriculture, but also through changing diets and increasing efficiency in the food chain. The unavoidable demand for phosphorus could then be met through a high recovery and reuse rate of all sources of phosphorus (crop residues, food waste, manure, excreta) and other sources including some phosphate rock. A 'hard-landing' situation could involve further fertilizer price spikes, increased waste and pollution (including eutrophication), increased energy consumption associated with the production and trade of phosphorus fertilizers, reduced farmer access to phosphorus, reduced global crop yields and increased food insecurity. A preferred 'soft landing' situation will however require substantial changes to physical and institutional infrastructure, including improved governance structures at the global, national and other levels, such as new policies, partnerships and roles to bring together the food, fertilizer, agriculture, sanitation and waste sectors for a coordinated response.

Finally, this thesis proposes a new global goal – *phosphorus security* – to be integrated in the dominant research discourses and policy debates on global food security and global environmental change. Among other criteria, phosphorus security requires that phosphorus use is decoupled from environmental degradation and that farmers' access to phosphorus is secured.

Keywords: *global phosphorus scarcity, peak phosphorus, global food security, sustainable resource use, food production and consumption system, transdisciplinary, systems thinking.*

CHAPTER 1: INTRODUCTION

In a world which will be home to nine billion people by the middle of this century, producing enough food and other vital resources is likely to be a substantial challenge for humanity. While past societies have demonstrated humanity's ingenuity, with their ability to invent, to substitute or even to adapt in the face of changing circumstances (such as agriculture's Green Revolution or medical advances like penicillin) we are now in an unprecedented era of global environmental change with substantial known and unknown implications for humanity. While there is certainly scope for further technological developments given the substantial inefficiencies in most of our current systems, these are unlikely by themselves to secure a sustainable future for humanity. Perhaps more concerning is the persistent uncertainty – what we don't know we don't know – and hence managing risks and complexity will be critical (such as the interaction between major challenges like climate change and agriculture). This is especially important for fundamental systems on which life depends – such as water, food, energy and the atmosphere. Foresight, re-evaluation of taken-for-granted assumptions and careful planning are required now to ensure these components of the 'earth system' are maintained and sustained to support future generations.

For the food system, this means ensuring access to (and knowledge of) nutritious food, as well as access to the natural resources (water, energy and nutrients) and human resources (soil science knowledge, labor, purchasing power) that are essential for producing food. While dominant discussions on global food security have captured many of these issues, one vital challenge has been largely omitted to date: future phosphorus scarcity. This thesis is about the story of phosphorus.

Phosphorus, together with nitrogen and potassium, is an essential plant nutrient. It is applied to agricultural soils in fertilizers to maintain high crop yields. Phosphorus has no substitute in food production, and therefore, securing long-term availability and accessibility to phosphorus is crucial to global food production. Phosphate rock – the main source of phosphorus today – has been responsible for feeding billions of people over the past century. However, phosphate rock is a non-renewable resource that takes approximately 10–15 million years to form, and production from high-grade reserves is likely to peak in the coming decades ('peak phosphorus'), despite increasing global demand. Due to a growing number of environmental, economic, geopolitical and ethical concerns, there is a need to reassess the way phosphorus is sourced and used in the global food production system.

CHAPTER 2: RESEARCH PURPOSE AND SCOPE

Global phosphorus scarcity linked to food security is an emerging discourse and field of research[2]. Whilst the price spike of phosphate rock in 2008 attracted significant attention to the situation, as little as three years ago, comments like "*If this was such a big deal, I would have heard of it by now*"[3] were not uncommon. Due to the infancy of this field relative to research on water or energy scarcity for example, much of the research presented in this thesis has been exploratory and purposefully broad (rather than narrow, fixed and deductive), in order to investigate the many complex and interrelated sustainability implications of global phosphorus use for food security.

This section outlines 1. the scope (including guiding principles and values), 2. the purpose of the doctoral research and 3. the structure of this thesis in developing the central argument.

2.1 Scope, guiding principles and values

This research focuses on the future sustainability of global phosphorus resources for human activity. Without phosphorus, there would be no life on earth. Phosphorus is an essential building block for all forms of life (including bacteria, plants, animals, and humans). In this thesis, food production (or nutrition) is argued to be one of the most significant roles of phosphorus in the human-activity system. Further, there is no substitute for phosphorus in crop growth, and hence food production (the significance of phosphorus is described in further detail in section 5.2).

The research on global phosphorus use presented in this thesis is explicitly linked to (and conceptually embedded within) the global food system. Due to global concerns regarding feeding a growing world population, coupled with increasing resource scarcity and pollution, the research has been guided in part by the principles of global food security (described in section 4.2). In this context, it is argued that phosphorus is most significant to global food *availability*, but also relevant to the dimensions of food *accessibility* and *utilisation*.

This research is also guided by the principles of sustainable development, first put forward in the Brundtland Report (World Commission on Environment and Development, 1987) and reiterated in the Friibergh Workshop on Sustainability Science (2000) in addition to numerous other dialogues on sustainable development (see Kates et al., 2005 for a review). The specific sustainability principles addressed in this doctoral research include:

- *intra-generational equity* – all members of the present generation have equal rights with respect to access to key resources (or the services/functions the resources provide). This includes (but is not limited to) the notion of farmer and household livelihoods (discussed further in section 4.2);

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[2] However as noted in chapter 5, in some sectors (such as the sanitation sector) there has been an awareness that the current sources of phosphorus are finite and this, together with the problem of eutrophication, is a reason to recover nutrients in sewage. However this awareness is far from mainstream, and research and policy have in most cases not been directly linked to global food security.

[3] This specific comment was made by a fellow scientist at the 2006 World Water Week conference in Stockholm.

- *inter-generational equity* – future generations have the same rights to access key resources. Therefore current generations have a responsibility to ensure such access to the resources of the services/functions they provide (discussed further in section 3.2.1);
- *ecologically sustainable development* – "*using, conserving and enhancing the community's resources so that ecological processes*[4]*, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased*" (Commonwealth of Australia, 1992). In this thesis, the physical Laws of Thermodynamics and Mass Conservation and ecological principles of thresholds and irreversibility are also important (discussed further in sections 4.1 and 4.3);

While the scope of this doctoral research is to address phosphorus in the context of global food security (the *primary* system boundary), it is not intended that it should remain as an isolated topic of investigation. That would indeed be contrary to the theory and practice of systems thinking. Important related topics such as eutrophication, other essential plant nutrients (for example nitrogen and potassium), or water and energy scarcity are within a *secondary* boundary and have been excluded from the primary boundary of this investigation, not because they are unimportant, but rather because they are already the focus of other investigations and research programs. The point is to further phosphorus scarcity research, so that it may be added and integrated with these other more established topics.

Section 3.2.1 discusses the scope (primary and secondary boundaries) in more detail, including what fields and analytical dimensions have been included, excluded and marginalized in this doctoral research and why.

2.2 Purpose

An overarching aim of this doctoral research is therefore to conceptualize and analyse the 'messy' global phosphorus problem situation in relation to global food security in a holistic way. 'Messy' problems are those in which there is often no consensus about the definition of the problem. They describe a controversial issue with multiple perspectives and conflicting stakeholder interests. Abeysuriya (2008) provides a succinct summary of literature on messy problems. The term 'problem situation' comes from soft systems thinking (e.g. Checkland, 2001) where a situation is perceived as problematical by an observer or participants in the situation. The term acknowledges that such situations are often complex, messy and the nature of the problem is ill defined (see sections 3.2 and 3.6.1 for further discussion). Conceptualization and in turn analysis of this messy problem situation does not imply the 'mess' will be simplified, nor does it imply consensus on the issue will be reached. Rather, the point is to reframe and analyze the situation in a coherent and systematic manner, to identify and analyse these tensions, lack of consensus and underlying possible explanations through the application of scientific methods. This research also explicitly seeks to contribute to sustainable improvements to the phosphorus problem situation.

The research questions addressed by this thesis are:

1) What are the sustainability implications of the current use of phosphorus for global food security, specifically, in what ways might the current approach to sourcing and using phosphorus depart from sustainability principles in the context of global food

[4] While this particular definition was prepared with a national scale in mind, in this thesis it refers to ecological processes on all scales, including local, regional and global.

security?

2) What can an analysis of the 'human-activity'[5] system reveal about the adequacy of the global governance and management of phosphorus, in relation to food security?
3) What improvements would be required, in relation to the current phosphorus situation to move towards global food security?

In this thesis, objectives refer specifically to the analytical means for answering the Research Questions. Specific objectives that facilitated answering the research questions were:

a) Primarily, to quantitatively and qualitatively analyze and conceptualize the sustainability implications of the phosphorus situation for current and future food security;
b) To analyze such implications for a significant national food production and consumption system;
c) To analyze the perspectives of key international stakeholders and the institutional arrangements and governance structures related to phosphorus sustainability in the context of food security;
d) To develop a goal and associated criteria for sustainable governance and management of global phosphorus resources for food security.

2.3 Thesis structure and central argument

While this doctoral research has been undertaken as a *cotutelle* (collaborative arrangement) between two universities (and indeed two countries), the thesis has been prepared in accordance with the Swedish thesis structure at Linköping University (that is, thesis by publication) in a way that also meets the thesis criteria set out by the University of Technology, Sydney.

While the papers provide most of the analytical basis for building the arguments, the roles of the chapters in this thesis are to further provide:

- synthesis of the entire research, main findings and conclusions;
- additional analysis (such as the institutional analysis);
- greater methodological and theoretical detail;
- a literature review and broader context to the analysis; and
- supplementary material (in the form of appendices for example).

The central argument of this thesis (figure 2-1) is built up through the five papers and chapters 4, 5, 6 and 8. While chapters 3 and 7 support the development of this argument by providing a theoretical and methodological basis for the scientific investigation. The remaining chapters and papers are therefore structured as follows (in terms of content and contribution to the central argument):

[5] According to Flood's review of Checkland's soft systems methodology, a human activity system "*is a systemic model of the activities people need to undertake in order to pursue a particular purpose*" (2000, p.727). In this thesis it is interpreted broadly to include actors, institutional arrangements and governance structures (see sections 3.6.1 to 3.6.3 for further explanations and definitions).

Chapter 3 is the main theoretical chapter, justifying and integrating the transdisciplinary research framework developed and applied to the entire study. Systems thinking has framed the entire research, linking methodologies that examine the physical and institutional dimensions of global phosphorus scarcity. Specific methods used in the analysis (including in the papers) are also detailed.

Chapter 4 sets the scene (provides broader context) for the arguments made in chapter 5, by identifying and critiquing three relevant global sustainability discourses: global environmental change, global food security and global resource scarcity. In addition to a critical literature review and setting the scene for chapter 5,6 and 8, this chapter demonstrates how phosphorus scarcity is fundamental to, yet currently absent from, all three global discourses.

Chapter 5 builds the main arguments of the thesis (from the analyses in *Papers I - V*) and presents the sustainability implications of phosphorus scarcity. This chapter builds the argument for why phosphorus is a globally critical resource, essential to food production (and hence long-term sustainable management is essential) yet currently far from sustainable in many dimensions. It identifies and conceptualizes multiple framings of phosphorus in society, predominantly related to the global food production and consumption system. This chapter explores and analyzes the current institutional structures governing global phosphorus resources in the food system (including actors, policies, worldviews). Following from chapter 4, this chapter argues and demonstrates how phosphorus scarcity is missing from the relevant global discourses which exacerbates ineffective governance.

Chapter 6 provides a synthesis of the findings from the entire thesis (that is, from chapter 5 and *Papers I-V*). This includes an integrated reconceptualization of phosphorus scarcity, an up-to-date assessment of knowledge sets following the rapid changes in 2008 (including levels of certainty and consensus). Finally, this chapter proposes and outlines a new global goal to respond to phosphorus scarcity – phosphorus security – drawing from the synthesis.

Chapter 7 picks up the justification for the theoretical framework from chapter 3, extending the validity of the transdisciplinary/systems research approach to one that contributes to 'intervention' (seeking improvements) in addition to just 'observation', (that is, contributes to the societal context in addition to peer-reviewed academic knowledge).

Chapter 8 provides concluding remarks and detailed research and policy recommendations following the findings.

Appendices provide qualitative and quantitative data, assumptions, methodology and other supplementary material supporting the thesis.

Paper I builds the argument that phosphorus is critical to humanity, yet becoming increasingly scarce and management is currently unsustainable. It analyzes the sustainability implications of global phosphorus scarcity for food security, including qualitative and quantitative analyses: 1. peak phosphorus, 2. a substance flows analysis of phosphorus through the food production and consumption system, and 3. African phosphorus flows analysis.

Paper II both contributes to the systems methodology in chapter 3, and structures a soft systems inquiry into the nature of the problem situation parallel to the analysis in *Paper I* and *Paper III*, and an analysis of the 'human activity' system, to better understand the structures, roles, relationships, and worldviews of the actors involved in the phosphorus system (brought together in chapter 5 and *Paper III*).

Paper III analyzes and synthesizes findings from in-depth international stakeholder interviews and draws on contextual material to better discern stakeholder perceptions about phosphorus and sustainability. It compliments and contributes to the argument that the current institutional arrangements and governance are ineffective. Policy implications are also drawn.

Paper IV follows on from and extends the quantitative analysis of the current situation and peak phosphorus analysis presented in *Paper I*, further building the argument that if phosphorus is critical for humanity yet the current system is unsustainable in many respects, substantial changes will be required to meet long-term future food demand. This paper provides a long-term global analysis of future scenarios for phosphorus for meeting global food demand. Probable, possible and preferred scenarios are developed for both supply-side options (such as manure, human excreta, food waste, crop residues, phosphate rock) and demand-side options (including changing diets, food chain efficiency and agricultural efficiency).

Paper V analytically explores the argument that findings from one geographical scale cannot necessarily be directly applied to lower scales. This chapter provides a case study of global phosphorus scarcity (as argued in *Papers I - IV*) for a net food-producing nation: Australia. This demonstrates the importance and significance of regional or national studies of the phosphorus problem. The findings are Australia-specific, however some general findings have been drawn for other regions (recommendations are made in chapter 8).

The following figure 2-1 indicates diagrammatically the development and causal linkages of the central argument, indicating which chapter and paper contributes to each node of the argument.

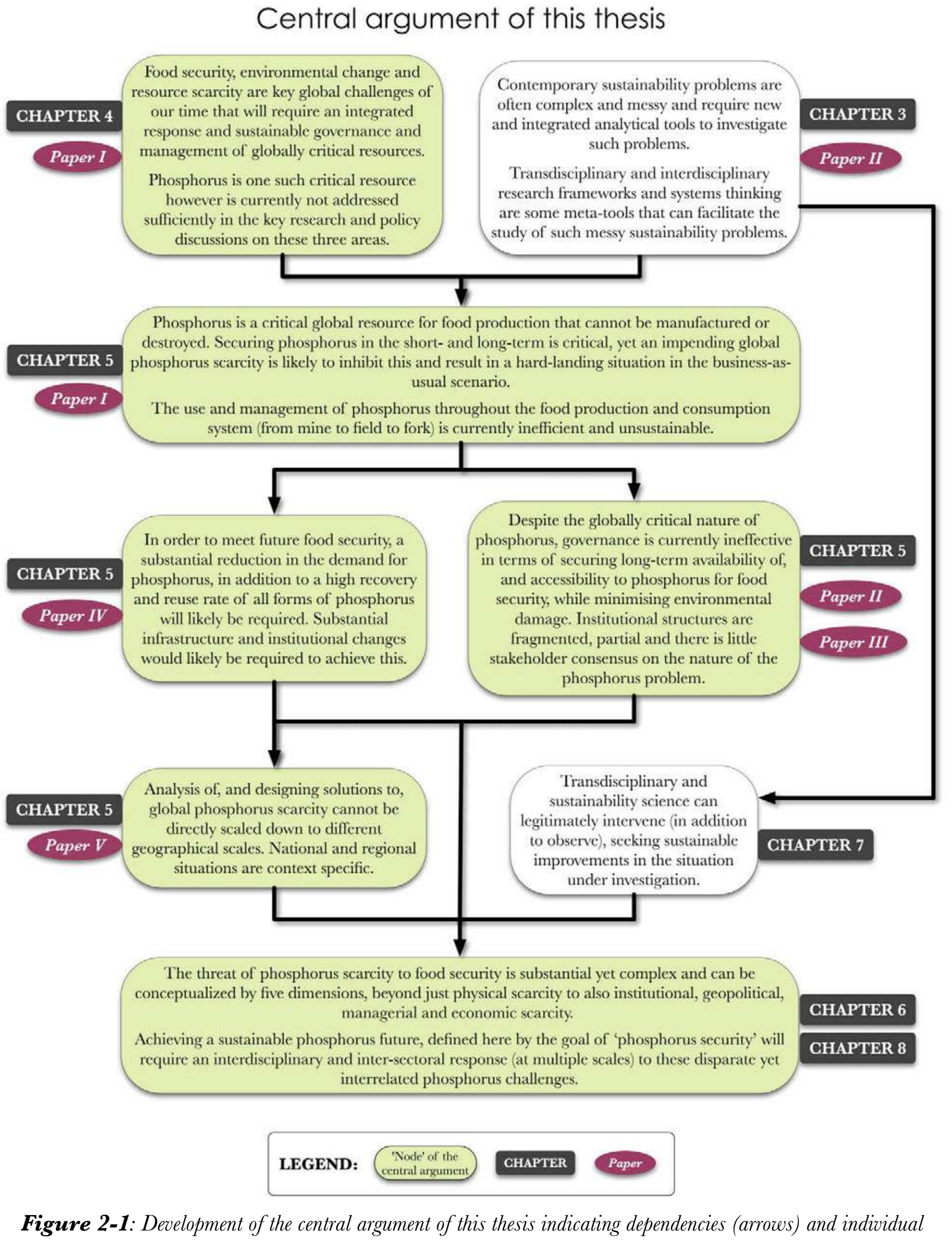

Figure 2-1: *Development of the central argument of this thesis indicating dependencies (arrows) and individual arguments (nodes). White nodes indicate theory/method related arguments. The chapter and paper associated with each node is indicated. Source: created for this research.*

CHAPTER 3: TRANSDISCIPLINARY RESEARCH FRAMEWORK: FROM THEORY TO METHOD

This chapter is the main theory and method chapter that provides the theoretical and analytical basis for the scientific investigation presented in this thesis. This chapter outlines and justifies the validity of the transdisciplinary research structure developed, from guiding theories and frameworks to the application and adaptation of methods and tools.

3.1 A transdisciplinary framework in an unprecedented era of global environmental change

3.1.1 Why transdisciplinarity?

Barack Obama put it simply in his presidential speech in 2008: "*the world has changed, and we must change with it*" (The New York Times, 2009). Will Steffen of the International Geosphere-Biosphere Program and Stockholm Resilience Centre articulated it with specific reference to sustainability: "*We are experiencing a very chaotic time, where humanity determines the outcomes for the Planet – Sustainability or collapse?*" (cited in Rockström, 2008). We are indeed in an era of unprecedented global environmental change: climate change, biodiversity losses, water scarcity, energy scarcity, a global food crisis and now a global financial crisis. Folke and Rockström call these 'turbulent times' (Folke and Rockström, 2009). Not surprisingly perhaps, the terms 'adaptive capacity', 'flexibility' and 'resilience' have become increasingly important terms of this era. These terms are today extended beyond their original ecological focus[6] to refer also to societies and institutions. The question of how humans and nature adapt to the uncertainty of climate change is an obvious example.

This resilience theoretical framework (described later in chapter 4) can be further extended to research and science programs, and the academic institutions that facilitate them. We can ask, how can we, as academic researchers, and our universities, doctoral programs and theses, adapt to these new challenges confronting us? Challenges that are more complex, global and fuzzy than ever. Indeed, the first international conference on resilience held a special workshop entitled '*Reorganizing Knowledge for Sustainability*' to reflect upon this very question (Resilience Alliance, 2008).

Another (re)emerging research approach or paradigm is *transdisciplinarity*. A logic here is that if the situation, theme or problem area under scientific investigation itself transgresses disciplinary boundaries, then research should have the capacity to adapt and transgress to respond accordingly. Today's theoretical frameworks and indeed institutions have developed in response to, and have emerged from, past situations (Vatn, 2005). Related to, yet fundamentally different from, *multidisciplinarity* and *interdisciplinarity*, transdisciplinary research aims to *transgress* disciplinary boundaries rather than combine or integrate disciplinary work (Robinson, 2008). In line with the OECD's (1972) original typology, Ramadier (2004) suggests that multi- and inter-disciplinarity respond to new challenges by looking for unity or synergies between disciplines, or by juxtaposing the principles or models from one discipline on to

[6] That is, the capacity of ecosystems to adapt, respond and renew in the face of external pressures in order to retain their integrity.

another, sometimes resulting in the development of a new sub-discipline[7]. He distinguishes transdisciplinarity from these other more disciplinary forms (figure 3-1) by suggesting the former aims to "*preserve the different realities and to confront them. Thus, transdisciplinarity is based on a controlled conflict generated by paradoxes. The goal is no longer the search for consensus but…the search for articulations*" (Ramadier, 2004, p434). Transdisciplinary research therefore creates new conceptual frameworks that synthesize methods and generate new ideas.

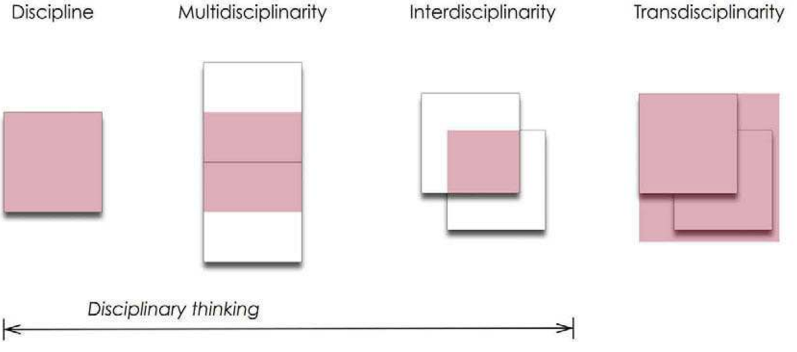

Figure 3-1: *Transdisciplinarity as distinct from disciplinary thinking associated with disciplines, multidisciplinarity and interdisciplinarity. Redrawn from Ramadier (2004).*

Russell et al. (2008), Mitchell and Willetts (2009) and Robinson (2008) identify key features of transdisciplinary research as:

- crossing, transcending or fusing disciplinary boundaries;
- contributing to multiple outcome spaces (peer review-academic knowledge, the context/situation, transformational change, including mutual learning) (detailed in chapter 7);
- a focus on breadth and discovery versus depth in a narrow field;
- responsiveness to the context;
- an evolving methodology;
- drawing on multiple sources of knowledge (such as reports, media, stakeholder views);
- co-learning between researchers and other stakeholders (for example a community of practice approach);
- acknowledgement or assessment of contradictions between disciplines, without the need to abandon the research altogether;
- different/new criteria for validity and research quality (see Appendix G); and
- effective communication to multiple and diverse audiences.

The departure point of most transdisciplinary research is a perceived real-world and socially relevant problem situation, hence the research can be said to be 'issue-driven' (Gibbons et al., 1994; Thompson-Klein et al., 2000; Wickson et al., 2006; Pohl and Hadorn, 2008; Robinson,

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[7] For example, the development of the sub-discipline of 'Industrial Ecology', which applies ecological analogies such as metabolism to the study of societies' production and consumption of resources, is described in section 3.5.1.

2008). Pohl and Hadorn note that such problem situations (what they call a 'problem field'), such as hunger, poverty, global environmental change:

> *are socially relevant when those involved have a major stake in the issue, when there is a societal interest in improving the situation and when the issue is under dispute. Those involved may agree neither on the relevance of the problem, nor on its causes, nor on the solution strategy required. Transdisciplinary provides knowledge for such kinds of situations"* (Pohl and Hadorn, 2008, p.112).

Engaging in the situation and with the stakeholders involved (for example, through action research[8]) is therefore almost a given in many forms of transdisciplinary research. Indeed, participants at the Friibergh Workshop on Sustainability Science noted "*scientists and practitioners will need to work together with the public at large to produce trustworthy knowledge and judgment that is scientifically sound and rooted in social understanding*" (Friibergh Workshop on Sustainability Science, 2000).

Transdiciplinary research for sustainability often aims to seek *improvements* in a situation perceived as problematic (Robinson, 2008). This understanding resonates nearly perfectly with the notion of 'wicked' or 'messy'[9] complex problems (Rittel and Webber, 1973; Ackoff, 1974) and indeed with the framework of soft systems methodology which aims to see acceptable accommodations through a structured comparison of the 'real world' mess with a conceptual ideal system (Checkland and Scholes, 1999) (as described and applied in *Paper II* and section 3.6.1).

Further, transdisciplinary research acknowledges that these problem situations tend to traverse multiple disciplinary boundaries and require research to respond to this setting. Indeed, in describing the resilience concept of social-ecological systems, Folke (2006) contends that it is not sufficient to address *either* social *or* ecological systems in the quest for sustainability. However, Ostrom (2008) observes that effectively addressing global environmental change *"is hindered because each of our disciplines has developed its own language and has developed its own definitions (sometimes multiple) for important concepts*" (p. 249). Figure 3-2 indicates the overlapping nature of these various frameworks and methods, as they relate to complex sustainability problems.

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[8] Action research is a reflective cycle of plan-act-reflect (Dick and Swepson, 1994). See chapter 7 for further details on how this approach has informed this doctoral study.

[9] See section 2.2 for explanation of 'messy' problems.

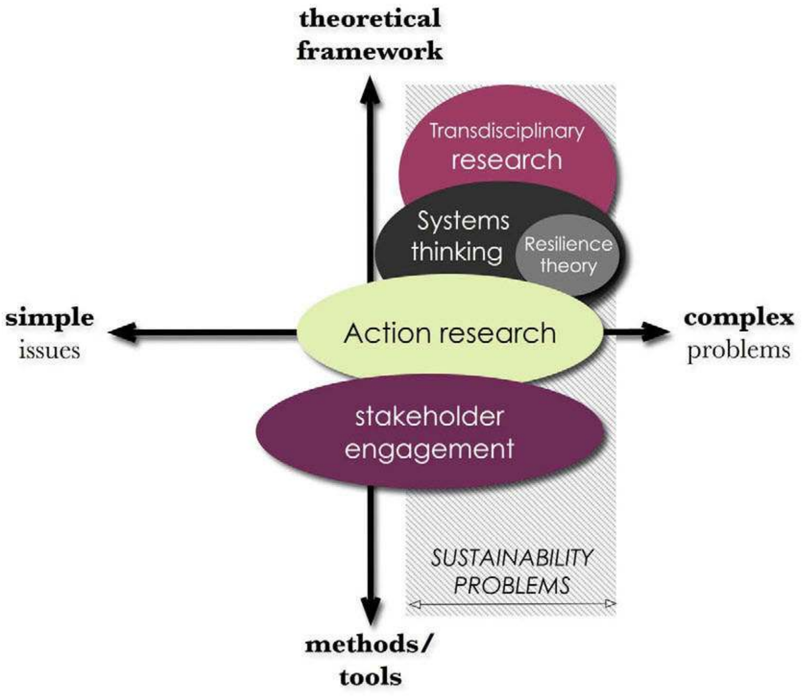

Figure 3-2*: The relationship between transdisciplinary research, systems thinking, resilience theory, action research and stakeholder engagement are indicated on the research hierarchy (y-axis) from theoretical framework to methodology to method[10]. These approaches are all useful for addressing sustainability problems at the complex, messy end (x-axis). Source: created for this research.*

Sustainability problems are complex and 'messy' almost by definition (see *Paper II*). Systems frameworks like soft systems methodology can be highly appropriate for addressing such messy problems (Checkland, 1999). Whilst the research frameworks and methods identified in figure 3-2 sit at different levels of the research hierarchy on the y-axis (that is, theoretical framework through to method), what they all have in common with respect to sustainability problems are the following features: a high level of complexity (and often persistent uncertainty), integrated analysis, lack of stakeholder consensus, no 'right or wrong' but rather 'good or bad', some degree of engagement with the context and reflection and review, no clear point at which a solution is reached and a concern with ethics (Dick and Swepson, 1994; Checkland, 1999; Folke, 2006; Palmer et al., 2007; Ison, 2008b; Pohl and Hadorn, 2008).

In addition to responding to new global challenges, crossing disciplinary boundaries can lead to discovery, innovation and yield new insights not always possible through disciplinary or multidisciplinary research. Discovery in this space is analogous to the property of 'emergence' in systems thinking (see section 3.2). That is, the whole is greater than the sum of the parts. Transdisciplinary research *complements* rather than competes with disciplinary research, through

[10] Other related fields not shown here include sustainability science (Bolin et al., 2000; Friibergh Workshop on Sustainability Science, 2000), and ecological economics (Daly, 1992).

its breadth and innovation. It is not the intention with transdisciplinary research to investigate a topic from a single narrow perspective in substantial depth, but rather to address the *interlinkages* between multiple perspectives to a moderate depth (Thompson-Klein et al., 2000).

This doctoral research is inherently and purposefully transdisciplinary in nature. That is, the problem situation itself crosses disciplinary boundaries, from physical and natural sciences (for example agronomy) to social and institutional fields (such as food security or governance) and hence demands a transdisciplinary framework. Such an approach enhances understanding of the problem area that would not be possible from the theoretical or methodological perspective of any single discipline.

What emerged relatively early on in the research was that the very fact that institutional structures have segregated the sustainability problems associated with phosphorus use from one another could be a reason why global phosphorus scarcity has been ignored by most scientists and policy makers for so long. That it was only when these constructed boundaries were transgressed and system inter-linkages were made that an incredibly powerful story of the phosphorus problem emerged. Therefore, a transdisciplinary and systems approach has been needed to address the phosphorus situation in order to make these inter-linkages clear and thus to demonstrate why, if discussions and appropriate actions are not initiated now, we are approaching another global environmental crisis that could affect the world's fundamental ability to produce food.

Closely connected with transdisciplinarity is the notion of epistemological pluralism. In order to discuss epistemological pluralism, it is instructive to revisit what is meant by epistemology. Epistemology is the theory of knowledge. As elaborated by Riedy (2008): "*Epistemology is the study of how we know what we know. It considers the ways in which knowledge is generated, the validity of knowledge developed in different ways and the assumptions that underpin different types of knowledge*" (p.2). Epistemology informs a researcher's theoretical perspective, which in turn informs the methodological approach (Crotty, 1998). Epistemological perspectives are most commonly conceptualized on a spectrum with subjective knowledge at one end and objective knowledge at the other. Objectivists essentially view the world as independent from the observer and hence believe that scientific research can be replicated and yield the same results, while subjectivists view knowledge production as inherently linked with the researcher and therefore believe that there can be no 'objective' truth waiting to be discovered.

As argued and applied here, epistemology can also encompass plural or integral perspectives, an approach which is particularly useful for transdisciplinary studies. The notion of 'epistemological pluralism' is supported by Healy (2003) and others (Midgley, 1992a; Wilber, 2001; Folke, 2006). Healy contends that:

> *'Epistemological pluralism' surmounts the constraints imposed by adherence to narrow representational perspectives, and the methods that attach to them, by legitimating and facilitating the deployment of other relevant perspectives and methods in parallel with them* (p.694).

Healy goes as far as to suggest such a plural approach can 'liberate' us from the constraints of 'epistemic sovereignty'. While making no claims of an emancipatory nature, Wilber (2001) and Reidy (2005) describe 'integral epistemology' as supporting the coexistence of objective and subjective approaches. Riedy explains that the former observes the exterior of structures, while the latter interprets the interior of structures (Riedy, 2005).

The transdisciplinary approach taken in this doctoral study draws from my belief that both objective and subjective approaches have a place in research as they answer different questions and hence can coexist. For example, phosphate rock can be viewed from an objective or a subjective perspective. An objective perspective might claim that the phosphorus content of phosphate rock is critical for soil fertility and that it is a limiting nutrient in crop growth (according to Liebig's Law, see section 5.2.1). While this may not be an absolute 'truth', I believe it has been a very useful guide or approximation for increasing crop yields worldwide to date and therefore has strong implications for global food production. At the same time, phosphate rock can have meaning from subjective perspectives. For example, among other meanings, phosphate rock has been ascribed a powerful or 'sacred' (Midgley, 1992b, 2003) status relative to other forms of phosphorus by certain actors and institutional structures. I believe achieving a more sustainable phosphorus situation with respect to food security could not be achieved by only addressing one perspective. Folke (2006) warns that one cannot assume for example that "*if the social system performs adaptively or is well organized institutionally it will also manage the environmental resource base in a sustainable fashion*" (Folke, 2006, p.260) (or vice versa).

In this way, my epistemological stance draws on 'post-positivist'-derived methodologies such as substance flows analysis, not because I believe in a single, objective truth waiting to be discovered, but rather because this approach is useful for answering some components of the research questions ('*what*', '*where*' and '*by how much*'). For example, this approach enables us to better understand: the nature of the physical limits of phosphate rock in the context of food security (while respecting uncertainty), the potential for other sources of phosphorus such as human excreta, and the magnitude of current system losses. On the other hand, approaches derived from more subjective interpretive frameworks are useful for answering the complementary questions of '*why*', '*who*' and '*how*'. For example a subjective approach is useful for exploring *why* phosphorus was not perceived as critical, to gain insights into the institutional arrangements and power relationships that influence the issue, and to identify what might be required to move towards a more sustainable future.

3.1.2 Current challenges for transdisciplinary research: critical reflections

While the transdisciplinary approach developed and applied in this doctoral research certainly yielded new insights regarding the situation under investigation, the process of investigation itself highlighted some challenges or tensions that still exist for transdisciplinarity (and indeed transdisciplinary researchers) in the wider research context. This section integrates critical reflections and recent transdisciplinary literature relating to current challenges, with particular focus on the issue of measuring validity and rigor.

1. Validity and rigor

The theory and practice of transdisciplinary research is still in its infancy (Wickson et al., 2006), and not fully understood or accepted by some disciplinary (or even multidisciplinary) researchers. This presents two immediate problems: a) demonstrating rigor and validity (by the researcher, in this case the doctoral student); b) evaluating rigor and validity (by the research community, or thesis examiner in this case) (Mitchell and Willetts, 2009).

The former (demonstrating validity and rigor) means extra work is often required in the thesis to explain and justify the approach. In this thesis, additional work was required to:

a. Introduce and demonstrate the legitimacy of transdisciplinary academic research to new or sceptical readers. This has included explaining what transdisciplinarity is, why it is appropriate for addressing sustainability problems, how it can be applied and how it might be measured;
b. Explain the innovative and integrated transdisciplinary approach that was taken in this

doctoral research. A number of methodologies were drawn upon and integrated through a systems analysis. Each of the methods and methodologies used has been introduced including explanations of why and how they have been applied. Some methodologies are also less well known (such as soft systems methodology), and hence some have been elaborated upon to demonstrate their appropriateness for addressing the topic of concern in this thesis;

c. Communicate to audiences from a range of disciplinary backgrounds. As with many transdisciplinary studies, the audience for this thesis is broad, and come from a range of disciplines and fields. Hence care has been taken to explain any terms that originate from a particular discipline or field in order to not exclude readers from other disciplines; and

d. Demonstrate both the legitimacy of contributing to multiple outcome spaces (beyond peer-reviewed academic knowledge) and the ways this has been carried out and achieved in this doctoral research (see chapter 7).

The latter issue (evaluating rigor and validity) means examiners can face a challenge when deciding the criteria by which to examine a transdisciplinary thesis. Following a discussion of Boyers' new forms of scholarship beyond 'discovery' (that is, the scholarship of 'integration', 'application' and 'teaching'), Schön asks in his paper "The New Scholarship Requires a New Epistemology": "but what are these kinds of knowledge, claims to validity, and criteria of appropriate rigour? And how do they stand in relation to the 'old' scholarship?" (Schön, 1995, p.27). Schön further observes that academic institutions (like all institutions) are not free of epistemological biases and that "they hold conceptions of what counts as legitimate knowledge and how you know what you claim to know" (p.27).

Indeed, even within different academic disciplines different criteria for validity exist, making the task of assessing transdisciplinary research challenging. For example, the more established positivist validity criteria designed for quantitative studies (internal validity, external validity, reliability and generalizability) are useful for more objectivist approaches (such as the phosphorus flows analyses and peak phosphorus curves presented in this thesis). However these criteria are not appropriate or relevant for most qualitative interpretative research. While several approaches to validity in qualitative research exist, Lincoln and Guba's (1985, cited in Goodrick, 2007) 'trustworthiness' criteria provide a somewhat appropriate framework for the nature of qualitative research components presented in this thesis (particularly the analysis of stakeholder interviews).

This trustworthiness criteria can be strengthened with systematic critical awareness as put forward by critical systems thinkers. For example, Ison (2008a) warns "*a risk is that a tradition can become a blind spot when it evolves into practice without critical reflection*" (p.2). Midgley (1996) offers a heuristic approach to foster critical reflection, for example suggesting: "*we should seek out the strongest possible 'enemies' of our ideas and enter into a process of rational argumentation. Only if we listen closely to their views and our arguments survive should we pursue the improvement*" (p.18). With these principles in mind, strategies to ensure rigor and validity that were employed throughout the analysis included:

1. Seeking rival explanations to 'test' if my chosen path of analysis was most appropriate. Perhaps the most important rival explanation in this context is that there was no phosphorus problem because the market assumption that scarcity is relative, because scarce resources can be substituted indefinitely and technological innovation will facilitate increased access and efficiency. This led to an analysis of how the current market-based system is not adequate to ensure the long-term sustainable management

and governance of phosphorus and the conceptualising of the five dimensions of phosphorus scarcity that go beyond the physical scarcity debate (chapter 6);

2. Negative case analysis to consider those situations that don't fit the general emerging pattern when analysing my interviews and other texts, which often shed light on the situation under inquiry (for example, strongly opposing views on phosphorus sustainability yielded the insight that multiple views on phosphorus co-exist and are not 'right' or 'wrong');

3. Triangulation – using a) multiple data sources (for example stakeholder interviews and literature), b) multiple methods (for example soft systems methodology and grounded theory), and c) multiple theories and perspectives to better understand areas of convergence and divergence;

4. Keeping a reflexive journal to document my reflections and analytical insights as I undertook each stage of the research. For example, I self-reflected on a set of questions immediately following each stakeholder interview (see Appendix B-3);

5. Peer debriefing and using a 'devil's advocate approach' by continually consulting peers, colleagues and mentors both inside and outside my field and disciplines to ''test' my emerging theories and approach. At the outset of this research study, the phosphorus problem situation was relatively ill defined and my transdisciplinary approach considered unconventional and therefore somewhat controversial. Therefore, I found it very useful (if not crucial) to test my approach on sceptics or 'devil's advocates' to seek their views and interpretation to consequently defend, modify or refine my approach accordingly. Indeed, because I engaged in the 'real world' context through publications, developing and updating a phosphorus website www.phosphorusfutures.net and through the media, many sceptical scientists and practitioners voluntarily delivered their criticisms both privately (through emails or face-to-face at conferences), or publicly (such as by posting their critiques of my and my co-authors' work on prominent public websites, such as Energy Bulletin – see for example Ward (2008)). Other critiques were also received indirectly when prominent researchers and other stakeholders were asked to comment on the findings of this research (particularly the concept of peak phosphorus);

6. Member checking with interview participants (and indeed those contacted for oral information) to ensure they were satisfied with how they have been presented in the quotes and write-up, and to confirm confidentiality prior to publication (see section 3.6.2); and

7. Communicating preliminary research findings with multiple and diverse audiences (including through the media) inadvertently ensured ongoing critical reflection by forcing me to ask 'what is the key message for this particular audience? How can I communicate my findings to this specific audience?". New insights were invariably formed during this process (see sections 7.2 and 7.3).

Measuring and evaluating validity and rigor in transdisciplinary research has been the focus of a recent study by Mitchell (2009) which concentrated on 'identifying, encouraging and evaluating quality' through action research. This study first involved a critical review of existing quality criteria to develop a proposed new set of more meaningful criteria for evaluating inter- and transdisciplinary research (see summary of this criteria in Appendix G). Secondly, the Mitchell study involved engaging a number of transdisciplinary scholars (including supervisors and doctoral students) to 'test' proposed new criteria and develop a resource toolkit of useful and innovative approaches for transdisciplinary students and supervisors. Indeed, the doctoral research presented in this thesis has both benefited from and contributed to the study[11] (Mitchell, 2009).

In essence, the new criteria recommend and stress: originality; critical awareness and reflection; engagement beyond the literature (for example with 'artefacts'); evolving methodology and communicating to a diverse audiences. The ways this doctoral research addresses the proposed criteria for assessing inter- and transdisciplinary doctoral research are demonstrated in the following points.

- **Original and creative contribution**: 1. at the time of commencing the PhD, there were no other bodies of work that address and analyze phosphorus scarcity linked to food security in a global, integrated way. Whilst this is now becoming an emerging discourse, the research on *broad* and *integrated* sustainability dimensions of phosphorus scarcity (and indeed phosphorus security) are still original; 2. the specific transdisciplinary methodology which gives equal attention to physical and human-activity systems (and their connectedness). That is, integrating soft systems methodology with institutional analyses, substance flows analyses and future scenarios was also unique (and hence required extra reflection and careful defence).
- **Critical awareness and reflection**: True to Churchman's call "*to expose our most cherished assumptions to the possibility of overthrow*" (Midgley, 1996, p.18), the systematic inquiry guided by soft systems methodology enabled me to recognize my original bias towards human excreta re-use as the main 'solution' to phosphorus scarcity. Indeed, I had entered the doctoral research inquiry with a specific research question '*To what extent can recirculating human waste from urban areas back to agriculture contribute to future global food security?*'. Two discrete incidents occurred that forced me to abandon the specific focus, despite a real research interest in that topic. Firstly, the development of the conceptual model in soft systems methodology requires 7 (±2) activities to undertake the system's defined 'purposeful activity'. The re-use of human excreta would not logically fit in to this system, unless the system was expanded to over 12 activities and included phosphorus recovery and efficiency at all stages of the activity chain. Secondly, the national case study revealed that human excreta represented only 2–3% of the total demand for phosphorus in Australia, and hence was not likely to be the single most important measure. One of my external mentors boldly observed "*oh that's interesting. So where does that leave your favourite method of re-using excreta?*". Hence, the focus on human excreta was reduced to sit alongside other sources of phosphorus (such as food waste).
- **Engagement beyond the literature**: Given the emergence of this field, it was not appropriate to focus on one type of data only. Literature and artefacts from technical/natural/social sciences, institutional reports, oral information, workshops and conferences, media and observations were all productively used (in line with Glaser's notion that "all is data" (*Paper III*) and as detailed in section 3.4.1.
- **Evolving methodology**: It became apparent in the first phase of the research that institutional structures were a significant barrier to the governance of phosphorus – it was not simply a question of physical/technical barriers or stakeholder perspectives, and hence the methodology needed to include an institutional analysis too. Further, as

[11] Professor Mitchell leads the postgraduate program at the Institute for Sustainable Futures at the University of Technology, Sydney, which encourages ongoing critical reflection by students and supervisors both individually and as part of a community of practice (see Willetts & Mitchell, 2006).

discussed in section 7.3, participant-observation became appropriate to respond to a changing context.

- **Effective communication for diverse audiences**: As demonstrated earlier, this research not only involved communicating to diverse stakeholder groups – research community, industry, government and the public, but also to audiences with substantially different views (ranging from those who felt my research findings were too conservative and 'aligning with industry' to those who believed the findings were too 'doom and gloom'). Indeed, reflecting upon and negotiating this delicate space facilitated the development of the terminology used in the synthesis of findings: phosphorus *security*, because this term (or frame) could accommodate and integrate multiple views while maintaining the integrity of the findings in terms of an improvement towards a sustainable future (see Appendix F-4 for further details of the strategic communication framework including assessment of contentious terms).

2. Mixed messages

The process of participating in many advanced international sustainability courses[12] witnessed many prominent senior sustainability scientists calling for interdisciplinary and transdisciplinary approaches and advising young researchers to "*be flexible!*", "*Be innovative, creative!*", "*Dare to jump outside your disciplinary box*". Yet these same mentors were simultaneously cautioning me against such transdisciplinary approaches because either: a) "*it is epistemologically/theoretically impossible to mix natural and social sciences in that way*", b) it's too risky, especially regarding examination, so better to 'play it safe', or c) quality is compromised, for example some expressed concern that one researcher can simply not be an expert in everything.

The first point (regarding transdisciplinarity and epistemological pluralism) is addressed throughout this chapter (particularly section 3.1.1). The second point (regarding the intention of this research to seek possible sustainable improvements) is addressed explicitly in chapter 7. Finally, the 'breadth versus depth' debate is a common criticism of inter- or transdisciplinarity (Robinson, 2008; Buanes and Jentoft, 2009). As argued throughout this chapter, the intention of this doctoral research is not a scholarship of depth in a specific, narrow discipline, but rather the 'scholarship of integration'. That is, through a critical systemic inquiry, identifying, conceptualizing and synthesizing connections across a broad set of disciplines and fields to more appropriately respond to the phosphorus problematique.

3. Disciplinary foundation versus 'meta'-disciplinary expert

Related to this, some mentors offered the advice that it is best to establish oneself or 'secure' a solid disciplinary foundation (for example I was advised to "*wait until you've got your PhD under your belt*") and then explore transdisciplinarity. However, is it possible this advice is more a reflection on the previous generation's approach to transdisciplinary and interdisciplinary research? (that is, perhaps there was little opportunity to explore transdisciplinarity a few decades ago). Further, if the purpose of the research (as is the case in this study) is to search for improvements to a perceived problematic situation, then the 'playing it safe' option may not result in the best improvement for the situation under investigation. Perhaps today's scholars

[12] Including: the '*Earth System Governance*' SENSE summer school in Amsterdam; the '*Early Career Resource & Environmental Economics Workshop*' in Bathurst, Australia; The '*Institutional Dimensions of Sustainability Problems*' Marie Curie THEMES summer school in Slovakia, the ACSPRI '*Qualitative Social Research Methods*' course in Canberra, Australia and the Wentworth Group of Concerned Scientists scholars' Master Class in Sydney, Australia.

can indeed establish themselves in 'meta-disciplinary' scientific approaches, as reflected by Pohl and Hadorn:

> *Is competence in [transdisciplinary research] developed in a personal dispute on alternative disciplinary approaches, based on a strong background in a home discipline? Or will the answer be that a new specialisation in science is under way around the three pillars of systems thinking and complexity science, participatory methods and knowledge management (Bammer, 2005), and that the scholar should better study those theories and methods?* (Pohl and Hadorn, 2008, p.112).

4. Transdisciplinary research requires transdisciplinary departments

While the *need* to cross disciplinary boundaries in sustainability research is becoming more accepted (as highlighted earlier), there are still largely unanswered structural implications for university departments. Drawing on Arts's (Arts and Buizer, 2008) framework of 'discursive institutionalism', a discursive shift alone is not sufficient; deep institutional change also requires a shift in actors, institutions and rules. In their analysis of institutional barriers to undertaking academic interdisciplinary research, Buanes and Jentoft (2009) conclude that:

> *any interdisciplinary approach will inevitably challenge, or be challenged by the regulative, cognitive and normative dimensions of established disciplines. Crossing disciplinary boundaries involves breaking rules, as well as questioning paradigms and norms, which are often considered to be inappropriate. It is therefore to be expected that those who do so will be met by some form of sanction* (Buanes and Jentoft, 2009, p.452).

While this doctoral research was fortunate to be based at two inter- or transdisciplinary research institutions: the Institute for Sustainable Futures in Sydney (which is independent of the faculties at the University of Technology, Sydney), and the Department of Water and Environmental Studies at the Tema Institute (literally translated as the 'Thematic' Institute), such academic institutional structures are not commonplace. It is a challenge to find a way for university departments, their learning, teaching and assessment frameworks and roles of academic researchers to adapt accordingly. Similarly, proponents of sustainability science highlight that fostering and supporting interdisciplinary research in the long term will require new styles of institutional structures (Friibergh Workshop on Sustainability Science, 2000).

3.2 Systems thinking: an overarching theoretical framework for transdisciplinary research

This transdisciplinary doctoral research is connected and framed by systems theory. Systems theory has been defined by some systems scholars and practitioners as a 'meta-discipline' (Checkland and Poulter, 2006) rather than a method or tool exclusive to any specific discipline, hence its appropriateness for transdisciplinary research. Further, systems thinking explicitly provides a mechanism to fuse or integrate the three so-called environmental, societal and economic 'pillars' of sustainability. For example, to provide a theoretical structure or framework to respond to the call of Sustainability Science to "*improve on the substantial but still limited understanding of nature-society interactions gained in recent decades*" (Friibergh Workshop on Sustainability Science, 2000, p.1). Before explaining the research approach taken in this doctoral study, it is instructive to first explain what is meant by 'systems thinking' and why it is seen as a useful frame in this context. The following general features define any complex system[13]:

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[13] Other relevant characteristics of complex systems are nonlinearity and persistent uncertainty. This is dealt with in chapter 4 in relation to resilience theory.

- **Interconnectedness**: systems are composed of interconnected entities, and indeed, all entities are directly or indirectly connected in some way (Ackoff, 1971; Midgley, 2003). The study of the interconnections or *relationships* between entities are often as or more important than the study of the entities themselves (Armson, 2007);
- **Boundaries**: any system has a system boundary as defined by the observer(s) (Midgley, 2003). The boundary may be defined in time, space or another dimension;
- **Holons**: any system contains sub-system components, and is simultaneously itself embedded within a greater system (its 'supra' system) (Koestler, 1973);
- **Emergence**: As put succinctly by Aristotle, 'the whole is greater than the sum of the parts'. Emergence acknowledges the significance of the relationships that exist between entities. Further, this relates to the notions of holons and hierarchy in that emergent properties exist at each level that were not present at lower level (that is, within the subsystems) (Gallopín et al., 2001; Armson, 2007); and
- **Self-organising**: In an ideal state, complex interactions within the system (subject to external forces) means it has the capacity to self regulate through feedback mechanisms (Holling, 1973; Folke, 2006). However in dysfunctional, unsustainable or vulnerable systems, the capacity to self-organise may be impaired. This is further discussed in section 4.1 regarding the resilience of social-ecological systems and in section 3.6.1 and *Paper II* regarding self-organising conceptual models in soft systems methodology[14].

These general features are applicable to both natural systems (such as the climate system) and human systems (such as an organisation or community) or integrated 'social-ecological systems' such as food systems (Folke, 2006; Ostrom, 2007). For this reason, systems thinking is applied in a wide range of fields from management science to cybernetics[15] to Earth System Governance (Biermann et al., 2009). Ison (2008c) provides a useful map of the development of systems theories and methodologies over time (Figure 3-3). This doctoral thesis is mostly influenced by the systems approaches in the top right corner (stemming from the system thinkers Flood and Jackson, Ulrich, and Checkland) and others not explicitly named in this diagram, including Ison (2008a), Armson (2007; Armson and Ison, 2008) and Midgely (Midgley, 1992b, a, 1996, 2001, 2003).

[14] As discussed later in this thesis and in *Paper II*, the current phosphorus-food system lacks resilience and the capacity to effectively self-organise. The sustainable improvements proposed in this thesis seek to increase the resilience of the system for example through the introduction of improved monitoring and feedback systems.

[15] Cybernetics is concerned with communication, feedback and control mechanisms in a system. It is applied in fields emanating from disparate epistemological perspectives, including mathematics and cognitive biology (see Ison, 1997).

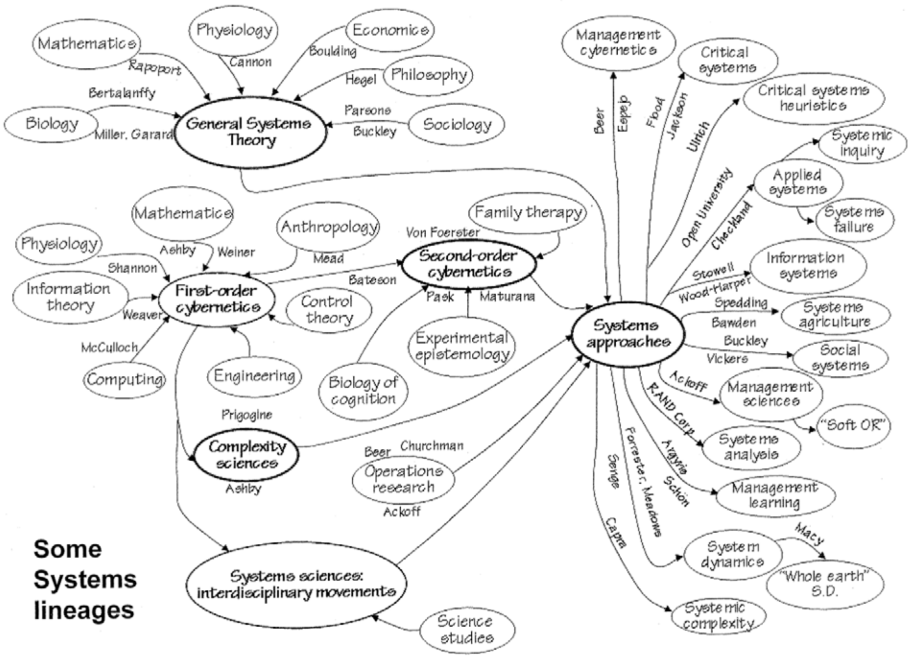

***Figure 3-3**: Interlinkages and influences of some systems approaches[16]. Source: Ison (2008c)).*

Some systems theories operating at a 'meta' level include General Systems Theory (Boulding, 2004) and Critical Systems Theory (Midgley, 1996). Critical Systems Theory (CST) is particularly relevant to the study of 'messy' or ill-defined problem situations, such as the one presented in this doctoral study, that have no obvious disciplinary home. While various streams of CST have evolved from Flood and Jackson (Jackson, 1987; Flood, 1989; Flood and Jackson, 1991; Jackson, 1991) and Ulrich (Ulrich, 1983) in the course of its history, it can be distinguished by three key features, following Midgley's interpretation (Midgley, 1992a, 1996, 2001, 2003):

a) **boundary critique**, including explicit critique of what is included, excluded and marginalized in the system. Drawing boundaries are inherently based on value judgements, hence the need to critically reflect on assumptions (and the values that give rise to them). See section 3.2.1 below;

b) **methodological pluralism** to acknowledge the strengths and weaknesses of various theories and methods that are appropriate in different contexts, and ensuring their cohesiveness and complementarity (for example through the use of a meta-theory[17]). Discussed in section 3.2 and elsewhere; and

c) an ethical commitment to **improvement** of the situation under study (where improvement implies creating change in a sustainable direction, that considers both

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[16] Other important systems approaches discussed in this thesis that could be added to the bottom right corner include 'social-ecological systems' (as part of the Resilience movement, e.g. Folke, Rockstrom, Ostrom), Earth System Science (as part of the Earth System Science Partnership, e.g. Leeman, Steffen).

[17] While acknowledging 'paradigm incommensurability' where appropriate (Midgley, 2000).

societal and ecological improvement in the long-term)[18]. See chapter 7.

In relation to the research hierarchy (epistemology, theory, methodology, method), systems thinking has both framed and been applied explicitly within this doctoral research at different levels. For example:

a) the theoretical framework was in part guided by the principles of CST;

b) soft systems methodology was used as a structured learning inquiry; and

c) while substance flows analysis and the institutional analyses applied specific systems methods to physical and institutional dimensions of the problem.

3.2.1 Scope and boundary critique

As highlighted earlier after Midgely, drawing system boundaries has strong implications for the nature of the identified improvements, hence explicit critique of both what is included and excluded from the system under inquiry is critical. This section therefore outlines and justifies the scope of this study (expanding section 2.1), including what has been included, excluded and marginalized and why. Figure 3-4 indicates the primary and secondary boundaries. Those issues within the primary boundary have been included within the analysis. Those depicted on the margin (boundary) are considered important to this topic under investigation, but have only been briefly included in the analysis, while those in the second boundary are considered important issues, but are outside the scope of this research.

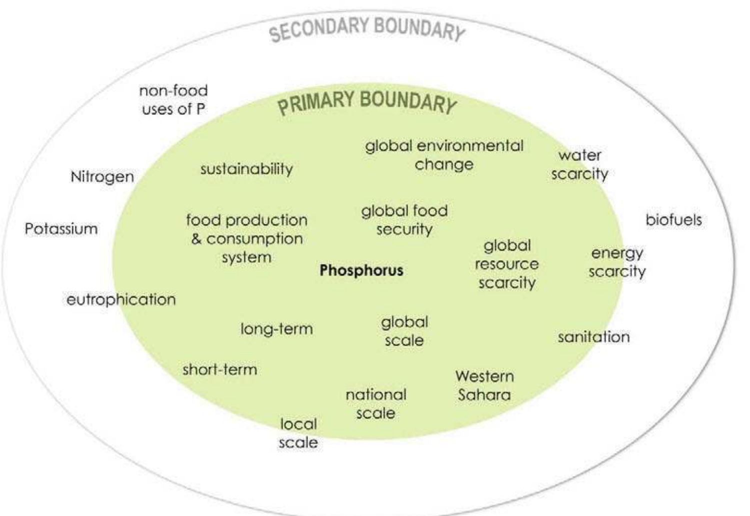

***Figure 3-4**: Primary and secondary boundaries of the research scope. Issues on the boarder have been marginalized not because they are unimportant, but because they are being addressed in other research fora. Source: created for this research.*

[18] Midgley (2001) notes what constitutes an improvement should not be taken for granted: "*Different stakeholders may have very different views on what constitutes an improvement, and some will be in a better position than others to express them*" (p. 619).

Explanation and justification of the relevant fields that were selected for inclusion in the analysis of the phosphorus problem situation:

- *Global food security* – food production is argued here to be the most important use of phosphorus in society, because there is no substitute for phosphorus in food production, and around 90% of the global use of phosphorus is for food production;
- *Global environmental change* – this discourse and body of research explicitly connects and addresses the human impact to global change and vice versa, through a systems perspective, which is highly congruous with the transdisciplinary and systems approach applied here;
- *Global resource scarcity* – phosphorus has commonalities with other resource use problematiques, and therefore it is constructive to explore discourses with a specific focus on characterising the nature of resource scarcity (among other sustainability concerns) for other globally significant resources (such as oil or water – energy and water scarcity);
- *Sustainability* – as noted in chapter 2, the study and objectives are explicitly guided by the principles of sustainability and further seek sustainable improvements to the current situation (of specific interest is ecologically sustainable development and inter- and intra-generational equity);
- *Food production and consumption system* – The entire food production and consumption system is included (rather than just mining of phosphate rock for example), to: a) allow connection of pollution problems and b) to understand losses and interlinkages (both physical and institutional) in the current system; and
- *Western Sahara* – the issue of Morocco's occupation of Western Sahara and control of its phosphate rock reserves is included, because a huge proportion of the world's agricultural fields are fertilized with rock from this region. There are two important dimensions here: a) an ethical dimension of consumers and companies knowingly or unknowingly supporting an occupation that breaches international human rights conventions (Corell, 2002; WSRW, 2007); and, b) the potential geopolitical consequences of a disruption of phosphate rock supply from the region.

Justifications for important marginalized or excluded issues include:

- *Nitrogen* and *eutrophication* – because their perceived problem situations are being addressed in other international academic and policy forums, such as the International Nitrogen Initiative (International Nitrogen Initiative, 2006; UNEP, 2007a) and the Helsinki Commission, HELCOM (www.helcom.fi), respectively.
- *Potassium* – has many similar attributes to phosphorus: a) it has no substitute in food production, b) current sources are non-renewable, and c) current sources are controlled by only a few countries. It is therefore possible that issues currently facing phosphorus will face potassium resources in the future. However, phosphorus resources are understood to be more physically scarce this century, hence the focus on phosphorus.
- *Sanitation* – was a starting point of this research, however the investigation revealed that while sanitation is indeed an important sector, other sectors/fields (such as urban organic waste, the impacts of diets, agricultural efficiency) are equally important. Therefore sanitation in this research is treated as being of equal significance to other sectors.
- *Biofuels and energy* – there are numerous energy-phosphorus linkages, including the

impact of increased biofuel production on phosphorus fertilizer demand. However, such issues perhaps deserve an entire separate analysis, and were considered outside the scope of this study.

- *Non-food uses of phosphorus* – since food is the main end-use of phosphorus (~90%), and indeed the principal one for which there is no substitute, this investigation has focused on food and excluded non-food or non-fertilizer uses of phosphorus.

In order to encompass important sustainability and ethical principles (such as intergenerational equity, long-term time frames, livelihood security, and ecosystem integrity), the system boundary in this doctoral research has deliberately been drawn wide to enable it to consider the wellbeing or status of:

1. **Multiple actors** throughout the food production and consumption system, including phosphorus producers (for example, the fertilizer industry), users (farmers), and beneficiaries (for example, households), For a discussion of which stakeholders were included/excluded, particularly for the international stakeholder interviews, see section 3.6.2;
2. Both **human** and **non-human** beneficiaries and victims (for example aquatic ecosystems, and the people of the occupied territory of Western Sahara); and
3. **Present** and **future** systems – in order to include both short-term dynamics and longer-term dynamics (related to future societies and the future state of the environment).

The following analytical dimensions were included in the research scope as follows:

1. **Geographical scales**: Findings from one scale cannot always be scaled up or down (Zurek and Henrichs, 2007). For this reason, an analysis of the global system (*Papers I, II, III and IV*) was complemented by a national system case study (Australian) (*Paper V*);
2. **Time scales**: Studying long-term time frames is of interest not just to explore where we are heading, but also to consider the question: where do we want to go? (Robinson, 1990). Short-term systems are nested within and can affect longer-term slower systems (Folke, 2006). Therefore, current (including short-term changes) and long-term future were analyzed (see *Paper I, IV* and section 7.5);
3. **Epistemological perspectives**: The phosphorus problematique has multiple dimensions that can be gainfully analyzed from both objective and subjective perspectives. Drawing on theoretical approaches from only one perspective may lead to partial conclusions. To facilitate the study of the problem situation from multiple perspectives, a transdisciplinary approach was taken that analyzed physical systems through a more objective, post-positivist[19] lens (*Papers I, IV, V*) and the human activity system – actors and institutions, by drawing on more subjective, interpretive[20] approaches better suited to answering the latter research questions (*Papers II, III,* and *V*), including the interconnections between the natural and human systems (for example through applying soft systems methodology (*Paper II*)).

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[19] Post-positivism here refers to a dominant stance in the physical and natural sciences that maintains a degree of objectivity, though unlike a pure positivist approach, acknowledges uncertainty and 'incomplete objectivity' through qualifications (Crotty, 1998).

[20] Interpretivism seeks to understand the different meaning structures through which people construct and interpret their world. This generally involves some form of participation by the researcher to identify the perspectives and values of those being studied (Crotty, 1998).

The analyses and their interrelationships are mapped in figure 3-5, indicating both how they relate to the three analytical dimensions described above, and to each other. The actual method(ologie)s applied in this study are each described in sections 3.5 and 3.6.

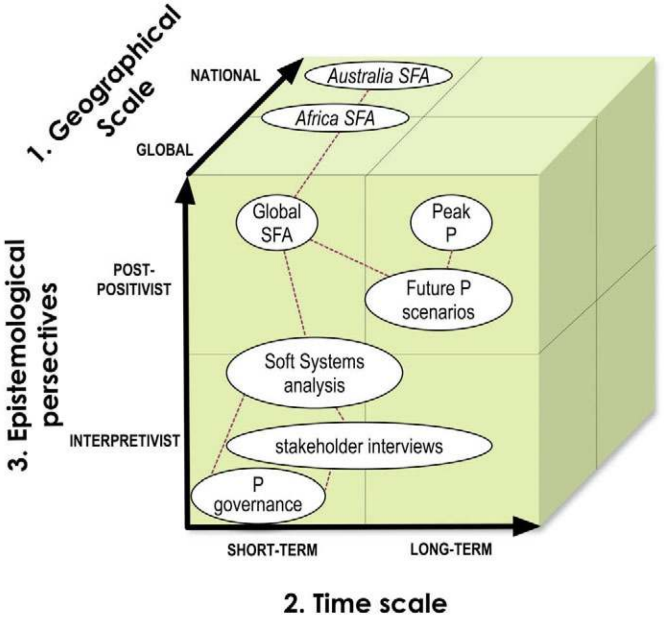

Figure 3-5*: Methodological framework indicating the scope of the analyses in three dimensions: 1) geographical scale (global to national), 2) time scale (short-term to long-term) and 3) epistemological perspectives (from more subjective perspectives (e.g. interpretivist) to more objective perspectives (e.g. post-positivist). Dotted lines indicate analytical connections between different components. Source: created for this research.*

3.3 Methodological framework

The methodology used in this doctoral research was evolving, transdisciplinary and informed by systems thinking, drawing on multiple data sources and multiple methods. This section outlines the theoretical/methodological framework that was developed to incorporate the study of scale, time and multiple perspectives on phosphorus, and outlines how the associated methods were adapted and applied.

The following diagram (figure 3-6) conceptualizes the interrelationships between the natural, physical and human activity systems (for a given time and geographical scale) that facilitate the methodologically plural analysis in this research. In their articulation of 'social-ecological systems' as an integrated concept of 'humans in nature' (Folke et al., 1998), Folke et al stress that "*the delineation between social and ecological systems is arbitrary*" (Folke, 2006, p.262).

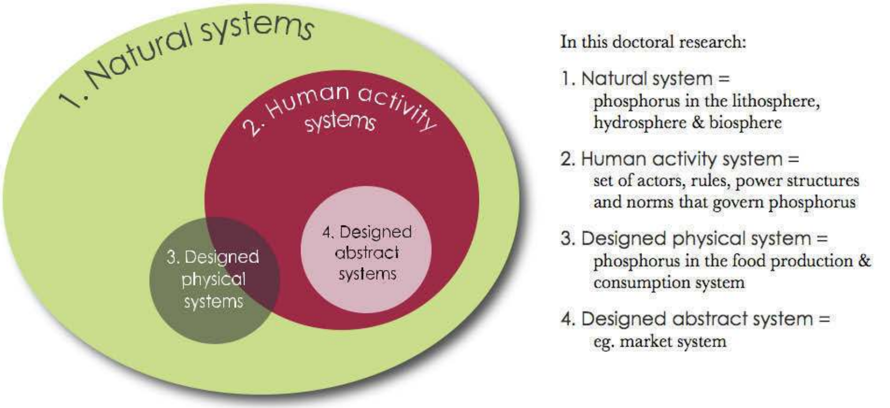

Figure 3-6*: Checkland's systems classification, indicating embeddedness and basic relationships between natural system, human activity system, designed physical system and designed abstract systems. Application to this doctoral research is also indicated. Redrawn from Zeibots (2007, in turn adapted from Checkland (1972)).*

The first focus of analysis in this research has been the *designed physical system* (3), in this case the global food production and consumption system and its interaction with the *natural system* (1), that is, the lithosphere and hydrosphere. This analysis drew on analytical methods such as Substance Flow Analysis within the field of Industrial Ecology (Graedel, 1996; Brunner and Rechberge, 2004) and future scenarios. The second analytical focus of this research was the *human activity system* (2), 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* (3), the *natural system* (1) and its subsystems, *designed abstract systems* (4) (such as the market system). This component drew from soft systems methodology (Checkland and Scholes, 1999), institutional economics (Young, 2002; Vatn, 2005) and qualitative social research methods such as grounded theory (Glaser, 1998).

Some researchers claim that the main distinguishing feature of a research methodology is whether it is quantitative or qualitative. They believe that the two approaches are grounded in conflicting epistemologies and cannot be combined[21] (Leininger, 1994). Others argue that such a distinction can hinder the creativity, reflexivity and flexibility of research design and that in fact combining the two in a scholarly manner can enhance research (Crotty, 1998; O'Leary, 2004). I subscribe to this latter view, aspiring to conduct research in line with O'Leary's suggestion that design be "*imaginative yet focused, intuitive yet logical, flexible yet methodical, ingenious yet practical*" (O'Leary, 2004, p.101).

In addition to the '*qualitative* versus *quantitative*' divide, other dichotomies also exist in methodological descriptions of scientific research, such as '*inductive* versus *deductive*', '*physical* versus *institutional*', '*soft* versus *hard*', and so on. In this thesis it is argued that such distinctions may over-simplify the situation and provide only partial explanations for transdisciplinary research. Often transdisciplinary sustainability research is neither one nor the other element in these dichotomies, but rather occurs as a combination of these to some extent. Hence these

[21] This tension led to the 'paradigm wars' in the early 1980s.

dichotomies are useful for classification rather a literal explanation of the research practice. For example, while peak phosphorus analysis is formally considered a 'quantitative' analysis of a 'physical' system, in this thesis the modelling is inseparable from geopolitical, ethical and other environmental questions which are not of a physical nature and are not easily quantifiable. Furthermore, the data itself is open to question and subject to politics and power-dynamics relating to transparency and knowledge production and knowledge management (as discussed in section 3.4.2).

Systems theory has therefore been applied as a means to overcome some of these constructed divides and to facilitate the transdisciplinary study. The methodology and methods described in the following sections are classified under the headings of *physical* and *human-activity* analyses, however these are in most cases inseparable and indeed most of the analyses described addressed interlinkages between the physical and institutional systems to some extent. In addition to being grounded in, or consistent with, systems thinking, these methodologies and methods were selected based on their appropriateness for investigating both the problem situation *and* possible solutions, that is, they were at least in-part solutions- or change-oriented. In-depth stakeholder interviews were considered of importance to yield primary qualitative data. Analytical tools such as discourse or content analysis may have been appropriate to answer some research questions, however were ultimately discarded due to their narrow benefit relative to size of the task and that they were limited to exploring existing discourses rather than extending to debate on what sustainable improvements could be made. Having said this, *discursive-institutionalism* is briefly touched upon in section 3.6.3.

Further, in most instances, the described methods were either adapted (for example *simplified* substance flows analysis is used) or their principles were drawn upon (for example the principles of grounded theory) to better suit the analysis of this problem situation, rather than a textbook application of each. In any case, the way each method or methodology was applied has been described.

Figure 3-7 provides an overview of the research process from data collection to analysis and how the research findings have been organized in both peer-reviewed papers and other complementary outputs.

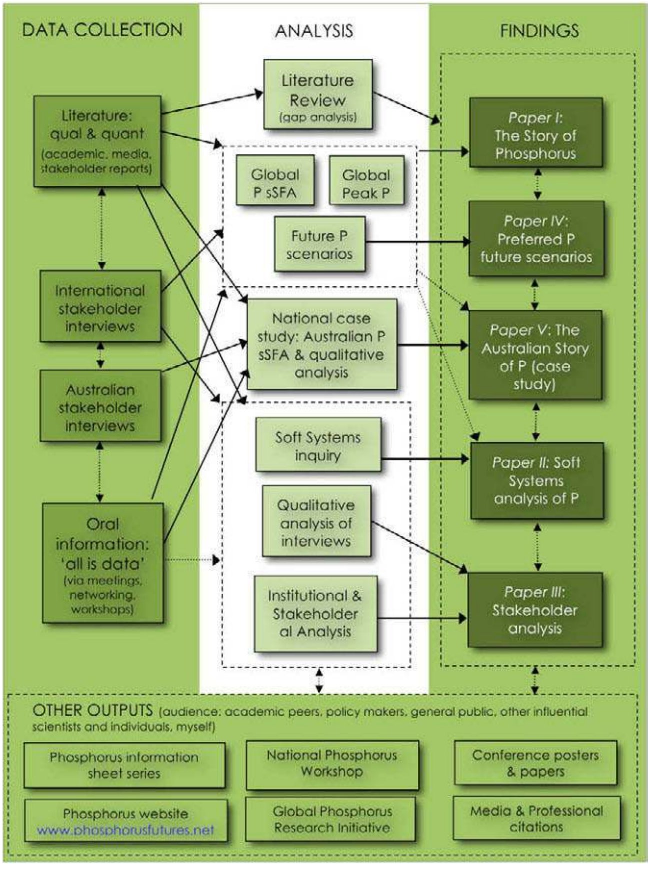

Figure 3-7: *Transdisciplinary methodological framework: from data collection to analysis to findings. Other outputs have also been indicated and are explained in detail in chapter 7. Source: created for this research.*

3.4 Data

3.4.1 Data sources

Due to the nature of this field shifting from near 'non-existent' in 2006 to 'newly emerging' in 2009, very limited data sets and analysis were publicly available. Consistent with the call of transdisciplinary research to draw on multiple artefacts beyond the literature (Russell et al., 2008), and indeed Glaser's notion that "all is data" (Glaser, 1998), data was sourced from a variety of sources and in a variety of ways. Qualitative and quantitative data were sourced through both primary and secondary sources and hence drew from multiple sources. This included secondary data (various forms of literature) and primary data (in-depth stakeholder interviews and other oral information). The triangulation of data is indicated in figure 3-8.

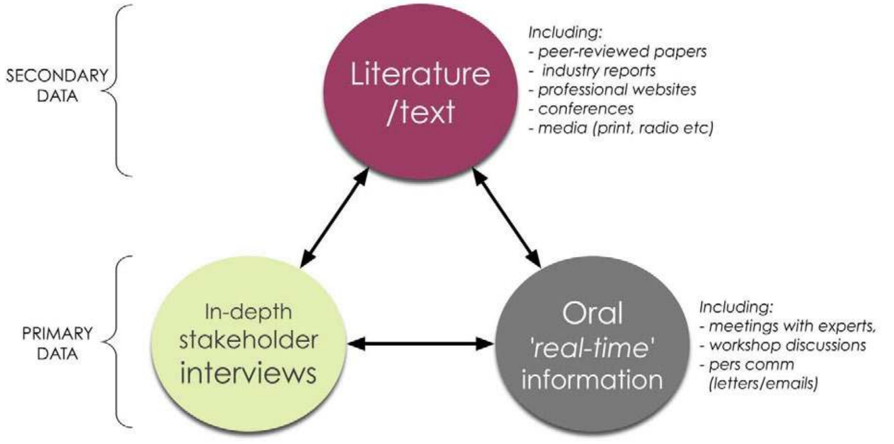

Figure 3-8: *Triangulating and supplementing data from primary and secondary sources. Source: created for this research.*

More specifically, these three categories of data included:

1. Secondary data: *Literature*: in line with Russell et al's observation that "*public forms of knowledge are becoming more legitimate*" (such as institutional websites) "*as other forms of knowledge are being privatized*" (such as market data which can be either confidential or available at extremely high prices) (Russell et al., 2008, p465), the term 'literature' was interpreted widely, beyond the peer-reviewed body of knowledge. Literature therefore included:

- Peer reviewed journal and conference papers;
- Reports (for example from UN bodies, international institutions, industry bodies, research networks[22])
- Conference presentations, papers and keynote speeches;
- Media (print, radio, TV); and
- Institutional websites and databases (scientific, governmental and industry).

Qualitative and quantitative literature was sought related to the fields[23] of: global environmental issues, sustainability, resource scarcity, sustainable production and consumption, global food security, global food production and consumption, sustainable agriculture, natural resource management, peak oil and energy scarcity, water scarcity, food waste, sustainable sanitation, nutrient cycles, health and diet, global phosphorus resources (largely excluding eutrophication issues), international fertilizer issues, phosphate rock resources and others.

[22] Special attention was given to research undertaken as part of the Earth System Science Partnership because several features were highly relevant to this doctoral approach, including: international/global dimensions, interdisciplinary, systems framework and social-ecological frameworks.

[23] Analytical themes such as systems thinking, transdisciplinarity etc. are described throughout this chapter, particularly sections 3.1-3.3.

While no central datasets were available for most phosphorus flows through the global food production system for the quantitative analyses in this thesis (such as the substance flow analyses and peak phosphorus analysis) (see Appendix A-1 and A-2), global environmental assessments (such as the Millennium Ecosystem Assessments) and other literature (such as Smil, 2000) were used as input to calculations, assumptions and analysis. Limited quantitative baseline global data sets that were available and utilized included:

- Phosphate rock (for example, from USGS, IFADATA);
- Fertilizers (for example, from IFADATA);
- Food (for example, from FAOSTATS); and
- Phosphate commodity prices (for example from the World Bank, USGS). Note that privatized knowledge such as market data from analysts such as CRU were not extensively sought due to the excessive associated costs as well as the availability of data from publicly available sources sufficient for this research.

Appendix A indicates the data, sources and assumptions used for the global and Australian phosphorus flows analysis and the long-term future scenarios. Specific data sources for the Australian case study are also discussed in section 3.7 and *Paper V*.

Further, 'real-time' textual data were sought due to the rapidly changing nature of the field under investigation. This meant data sourcing was an ongoing exercise throughout the study. To ensure up-to-date observations as the food crisis unfolded, Google-alerts were actively used for a period of three years for the search terms 'phosphorus', 'peak phosphorus', 'fertilizers', 'fertilisers', 'phosphate'. This yielded any publicly available information on the internet, ranging from governmental reports to press clippings. Often 15–30 alerts were received on a daily basis. Other means to ensure up-to-date data included periodic monitoring of journals and key stakeholder websites for new publications or position statements, and a growing network of researchers and practitioners who on-send information. This process was often triangulated. For example, almost all data I received from the growing networks, I had already picked up via the Google-alerts data collection process.

2. Primary data: *In-depth stakeholder interviews*:

- six international stakeholder interview recordings, transcriptions and observations; and
- two Australian stakeholder interview recordings, transcriptions and observations.

These are discussed in detail in section 3.6.2 and *Paper III*.

3. Primary data: *Oral information*:

- Meetings with experts – In addition to conducting semi-structured stakeholder interviews, I visited a number of targeted stakeholders organisations both in Australia (for example various relevant CSIRO departments) and Europe (such as researchers at Plant Research International at Wageningen University in The Netherlands) to further discuss qualitative and quantitative data and views;
- Workshops – such as the discussions and material outcomes from the Australian National Phosphorus stakeholder workshop;
- Phone conversations, letters/emails – I contacted targeted stakeholders for specific information via email or phone where little literature existed (for example, data and literature on the re-use of organic fertilizers on a national scale in Australia is near non-existent, hence the head of the Organic Federation of Australia was contacted to obtain

access to the limited oral or grey knowledge). In addition stakeholders voluntarily sent me information, including for example a hand-typed seven-page letter documenting relevant research and events that took place over 50 years ago.

The multiple data sources were used to triangulate data in some instances (such as estimates on remaining phosphate rock reserves), or to supplement in other cases (for example, the worldviews were drawn by combining data from the stakeholder interviews and a literature review).

3.4.2 Data scarcity and accountability

As mentioned previously, there are substantial concerns regarding the scarcity of phosphorus data, including: a lack of raw data, data uncertainty, lack of accountability, lack of transparency of knowledge production and knowledge management and power imbalances between current data producers and data users.

The Earth System Governance (ESG) program describes *accountability* as one of five important analytical themes (Biermann et al., 2009). Closely connected to legitimacy, ESG scientists note the focus in the 20th century was traditionally on the accountability of nation states. Transparency is understood as one mechanism to ensure accountability and legitimacy in global environmental governance based on the premise that knowledge can empower (Gupta, 2008). However Gupta (2008) suggests there is *"a compelling need to investigate the growing pervasiveness of the call for transparency in global environmental governance, one which extends beyond state-led international environmental regimes to private and market-based governance as well"* (Gupta, 2008, p.1). In terms of knowledge production, this is consistent with Russell et al's observation (as noted above) that some forms of knowledge are becoming privatized. Such privatized knowledge (related to a resource essential for humanity) is concerning. In the context of phosphorus and food production, accountability and transparency related to the main phosphorus knowledge producers today – the fertilizer industry and the USGS, is a key question.

The following sections discuss the nature of data scarcity with specific reference to information on phosphate rock, other phosphorus flows through the global food production and consumption system and the question of future demand. As observed at the recent World Resources Forum, this issue of data scarcity is not unique to phosphorus resources, but extends to the stocks and flows of other scarce and globally significant resources and precious metals (for example, Chancerel and Rotter, 2009). Recommendations for improved data reliability, accountability and management are provided in the research recommendations in chapter 8.

Phosphate rock

Of all sources of phosphorus (which include manure and crop residues), most data is available for phosphate rock. However there is still a concerning scarcity of reliable, transparent, independent data on phosphate rock reserves, resources, time series price trends and production. This data is important for estimating a peak phosphorus timeline (and other depletion scenarios) and short-term availability. Some dimensions 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);
- *Economic*: Inconsistent economic assumptions behind what constitutes a 'reserve'. USGS

notes that each country/company uses different assumptions such as $/tonne;

- *Commercial*: Data which 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 centre, 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 (Geoscience staff, pers comm. 30/01/08);
- *Privatized knowledge*: Some commercial data is available, at very high cost – for example a subscription to the comprehensive *Fertilizer Week* statistics costs 2,850 Euros[24]. 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 the only organisations that produces 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 completely missed the 2008 price spike (World Bank, 2008);
- *Geopolitical*: For example, China's reported reserves doubled over night when it joined the World Trade Organisation. Further, in 2007, reported world reserves totalled 18 000 million tonnes, while in 2008 they decreased to 15 000 million tonnes, largely because China altered its reported reserves, and Australia increased its reserves moderately (Jasinski, 2008, 2009); and
- *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.

Table 2 of *Paper I* and section 3.5.2 identify and discuss some of the reasons for the variance in data reliability specifically related to the peak phosphorus analysis.

Phosphorus flows through the food production system

In relation to other sources of phosphorus (such as manure, excreta, crop residues and household organic waste) very little reliable data was found. Important data here relates to the annual use, losses and re-circulation within the food system. These organic phosphorus sources are typically not commodities, and are applied informally and on an ad hoc basis, and so there is little formal tracking of their use and losses. For example, there is a negligible amount of data collected on organic sources of phosphorus (such as manure) in Australia, as noted earlier. Data that does exist is typically compiled at a farm or local level.

The use of organic phosphorus sources is often not quantified in investigations of phosphorus flows in the food production and consumption process as researchers have been more interested in losses to water bodies causing eutrophication. However, even the exact magnitude of phosphorus losses from agriculture and other land (via erosion) are difficult to measure due to the diffuse nature of erosion. It is estimated that only approximately 10–20% of phosphorus

[24] See http://www.cruonline.crugroup.com/FertilizersChemicals/FertilizerWeek/tabid/177/Default.aspx.

in fertilizers is taken up by crops in the year that it is applied, while a much smaller percentage is taken up in subsequent years. Further uncertainty therefore occurs because: a) crops are also taking up phosphorus from the soil 'stock' that has built up from previous fertilizer applications and from natural soil phosphorus, and b) that which is not taken up by crops either remains in the agricultural soil, or is lost via erosion to water bodies or non-agricultural soils. The magnitude of the soil stock is important because it can be considered a future source of plant phosphorus and will therefore reduce the demand for applied fertilizers. For example, almost 10 years ago, CSIRO soil scientists in Australia estimated that Australian soils could hold approximately A$10 billion worth of phosphorus (CSIRO, 1998). More recently this 'stock' has been estimated at around 100kg P/ha. As noted in *Paper V*, substantial research on how to 'unlock' this phosphorus (in addition to other measures for better managing phosphorus) is currently underway.

Future phosphorus demand

Finally, there was also a concerning lack of data regarding long-term future projections and future scenarios of phosphorus. For example, there are no reliable long-term forecasts for the demand for phosphorus fertilizers, beyond five-year industry (IFA) and FAO 2015 and 2030 forecasts for mineral fertilizers derived from phosphate rock (FAO, 2000). Importantly, these forecasts only consider phosphate rock on the supply side, and assume a business-as-usual demand, hence ignoring the 'silent' yet important demand from poor farmers with infertile soils who cannot currently access the fertilizer market due to their low purchasing power. Such information is critical for planning for long-term food availability and accessibility.

3.5 Methodology for analysing the physical system

To analyze the current significance of phosphorus in the food production and consumption system, the following methods were applied:

1. Substance flows analysis (from industrial ecology);
2. Peak phosphorus analysis (from Hubbert's peak theory); and
3. Future scenarios (from future studies).

These predominantly quantitative methods were used to address in part the research questions "What are the sustainability implications of the current use of phosphorus for global food security?" And "What improvements would be required, in relation to the current phosphorus situation to move towards global food security?".

3.5.1 Substance Flows Analysis (SFA) and Industrial Metabolism

Ayres (2002) coined the term 'industrial metabolism' in 1989 to refer specifically to the material or energy flows through an industrial society. This compares to social metabolism which more broadly addresses to the metabolism of any mode of social structure (industrial, agrarian or hunter-gatherer) (Fischer-Kowalski and Huttler, 1999). The field is embedded in industrial ecology, an approach that envisages sustainable industrial activity where "*the use of energy and materials is optimized, wastes and pollution are minimized and there is an economically viable role for every product of a manufacturing process*" (Frosch and Gallopoulos, 1989, p.7). Indeed, the Chinese central government has gone as far as developing concepts for a 'Circular Economy' which has its basis in Industrial Ecology (Yuan et al., 2006).

A key tool in this field is substance flows analysis (SFA)[25] first developed as 'material flows analysis' by Brunner and Baccini in the early 1990s (Brunner and Baccini, 1991). SFA is a material accounting tool that helps assess and understand the sustainability of a particular material in the environment whose quantity and flow paths have been altered by human activity. It quantifies the inputs, outputs and accumulation of a given material or substance from processes and stocks within a system (figure 3-9) to better understand pollution loads on a given environment, and determine places to intervene in a system to increase its efficiency, or reduce wastage and pollution (Brunner and Rechberge, 2004). This is a highly appropriate method for investigating the global supply and regional distribution of available nutrients such as phosphorus in the entire food chain and the demand for nutrients in agriculture.

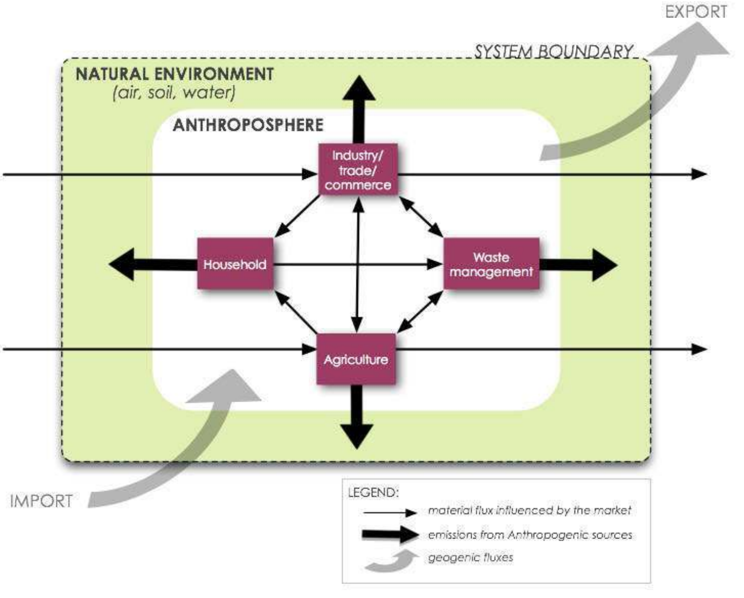

Figure 3-9: *Conceptual substance flows analysis diagram showing the interactions between the 'anthroposphere' (human activity system) and the natural environment. Redrawn from Brunner and Baccini (1991).*

Numerous studies in Europe, Asia and Australia have now been undertaken that examine the anthropogenic flow of phosphorus at different scales, including:

- A country (Gumbo, 2005; Liu, 2005; Schenk et al., 2009);
- A city (Hendriks et al., 2000; Neset, 2005; Tangsubkul et al., 2005; Huang et al., 2007; Montangero et al., 2007);
- A water catchment (Lambert and Brunner, 2000; HELCOM, 2005; Mörth et al., 2007);
- farm scale nutrient budgets (Smaling et al., 1996; Granstedt, 2000); or

[25] Previously known as Material Flows Analysis, SFA now refers to 'substances' (e.g. elements) rather than 'materials' (e.g. food, water).

- historical societies (Fischer-Kowalski, 1996; Fischer-Kowalski and Huttler, 1999; Cordell, 2001; Neset, 2005).

A primary driver for many of these studies was phosphorus pollution from anthropogenic sources that was perceived to be unacceptable (as discussed in section 5.4). Through quantification of phosphorus stocks and fluxes (for example in terms of kilograms per year) associated with each process in a given societal boundary, effective intervention points for the management of phosphorus could be determined. For example, an SFA study of phosphorus in Kunming, China, indicated that not only was human excreta the main source of phosphorus, but the failing sewerage system (including sewerage overflows, infiltration and other losses) was by far the largest flow of phosphorus to the polluted lake. Therefore the only effective intervention point would be at source (that is, at the toilet) or the entire pipe network would need to be rebuilt (at significant cost) (Huang et al., 2007).

While many of these studies mention or acknowledge the finiteness of global phosphorus resources in a general or conceptual sense (for example it is mentioned in the background or introductory sections of some papers), their analysis and findings have not been explicitly extended to implications for the food system at the global scale. Two important studies which have examined the global phosphorus cycle include Smil (2000b) and the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005a). However these focused more on the interactions *between* the lithosphere, hydrosphere, biosphere and anthroposphere, rather than on details *within* the anthroposphere. Smil's modelling of "*Phosphorus in the Environment: Natural Flows and Human Interferences*" (2000) has therefore been taken one step further in this doctoral research to estimate phosphorus flows in the global food production and consumption system. The specific intention here is to determine the magnitude and location of current phosphorus losses, and hence the potential for altering the demand for phosphorus, and increasing efficiency and recovery at various stages in the food system.

The simplified SFA presented in figure 5-8 (chapter 5) and figure 3 (*Paper I*) traces phosphorus through the global food production and consumption system, from the mine through to consumption, and identifies losses throughout the system. Unlike water (SIWI-IWMI, 2004; Lundqvist et al., 2007), carbon (GCP, 2008) and nitrogen (UNEP, 2007a), there are no comprehensive studies analysing anthropogenic global flows of phosphorus[26]. This means there was very little baseline data available on which to base a detailed quantitative study and hence the analysis here has been termed a 'simplified' substance flows analysis. This also means the figures are indicative rather than precise.

In addition to the global phosphorus flows analysis, an Australian study (see figure 4 in *Paper V*) and an African study (see figure 2 in *Paper I*) were also undertaken, to exemplify regional and national implications. Findings from the global scale cannot be scaled down to these lower levels; rather, they indicate the importance of local studies to yield contextual findings. Key findings from these analyses are presented in *Papers I* and *V* and Section 5.4. Assumptions, data sources and uncertainty issues for the simplified phosphorus flows analyses are presented in section 3.4.1 and Appendix A.

[26] A paper published during the writing of this doctoral study by Liu et al. (2008) also provides an analysis of global anthropogenic phosphorus flows based on existing data.

3.5.2 Peak resource production curve

Understanding the longevity and quality of future phosphate rock reserves is critical to this study, given humanity's current dependence on this non-renewable source of phosphorus. While estimates of remaining reserves range from 50–100 years (*Paper I*), increasing understanding of peak theory means the critical point could indeed occur decades before these depletion estimates. As described in section 4.3.1 and *Paper I*, in a similar way to oil reserves, the rate of global production of high-grade phosphate rock will eventually reach a maximum or 'peak', based on the finite nature of non-renewable resources. Hubbert (1949) and later others argue that the important period is not when 100% of the reserve is depleted, but rather when the high quality, highly accessible reserves have been depleted. After this point, the quality of remaining reserves is lower and they are harder to access, making them uneconomical to mine and process. Therefore while demand continues to increase, supply decreases year upon year.

The conservative peak phosphorus analysis using industry data, suggests that the peak in global phosphorus production could occur by 2035 (details presented in figure 4 and surrounding text of *Paper I*). This analysis of peak phosphorus is based on estimated phosphorus (P) in current world phosphate rock reserves (approximately 2358 million tonnes P) based on US Geological Survey data and cumulative production between 1900 and 2007 (totalling 854 million tonnes P) based on US Geological Survey data (Buckingham and Jasinski, 2006; Jasinski, 2007; Jasinski, 2008) and the European Fertilizer Manufacturers Association (European Fertilizer Manufacturers Association, 2000). The area under the Hubbert curve must equal the depleted plus current reserves, totalling approximately 3,212 million tonnes P. Units of phosphorus are presented as elemental P, rather than P_2O_5 (containing 44% P) or phosphate rock (containing 29–34% P_2O_5) as commonly used by industry.

The data for production is fitted using a Gaussian distribution[27] (Laherrere, 2000), based on the depleted plus current reserves estimate of 3,212 million tonnes P, and a least-squares optimisation which results in a production at peak of 28 million tonnes P/a and a peak year of 2033. Data sources of uncertainty were described in section 3.4.2 and in *Paper I*.

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, OPEC fixing annual production in the case of oil);
    - Geopolitical instability in a producing nation can reduce annual output;
    - Input constraints (such as the price of oil or sulfur) can reduce annual production;
2) Demand-side variables (can increase or decrease demand):
    - Deliberate market distortions by major producing nations (such as China's export

[27] The actual mathematical analysis was undertaken by my doctoral supervisor Professor Stuart White.

tariff in the case of phosphate rock which further increased the price of phosphate rock thereby reducing short-term demand of the commodity);

- Global or regional economic booms or crashes (for example the 2008-9 global economic downturn was thought to be responsible for a reduced demand in phosphate rock, while the collapse of the Soviet Union in 1989 lead to a sudden drop in demand from a major phosphate consuming country);
- 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
- 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 put forward in chapter 5, there will always be a demand for phosphorus for food production for which a corresponding supply will be required.

3.5.3 Future scenarios: probable, possible and preferred futures

Projecting business-as-usual into the future (through forecasting) has traditionally been the most common form of future analysis to determine where we are likely to be heading. Scenarios, on the other hand, provide images of possible futures situations, rather than an expected or probable future. Wollenberg et al (2000) further explains:

> *scenarios aim to stimulate creative ways of thinking that help people break out of established ways of looking at situations and planning their actions...Scenarios are useful tools where complexity and uncertainty are high* (2000, p.2).

Addressing sustainability problems typically shrouded in complexity and uncertainty often requires the development of multiple and integrated scenarios. Swart et al. (2004) articulate such integrated scenarios for sustainability science as "*coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems*" (Swart et al., 2004, p.139).

In order to develop scenarios about a sustainable future, it can be instructive to first clarify a future vision. Backcasting is a useful tool for formulating a future shared vision, by asking "*where do we want to be in the future?*" and temporarily ignoring the challenges of the present that often constrain planning and decision-making. While forecasting projects a present point into the future, backcasting works backwards from a specified preferred future to the present (Dreborg, 1996). See figure 3-10.

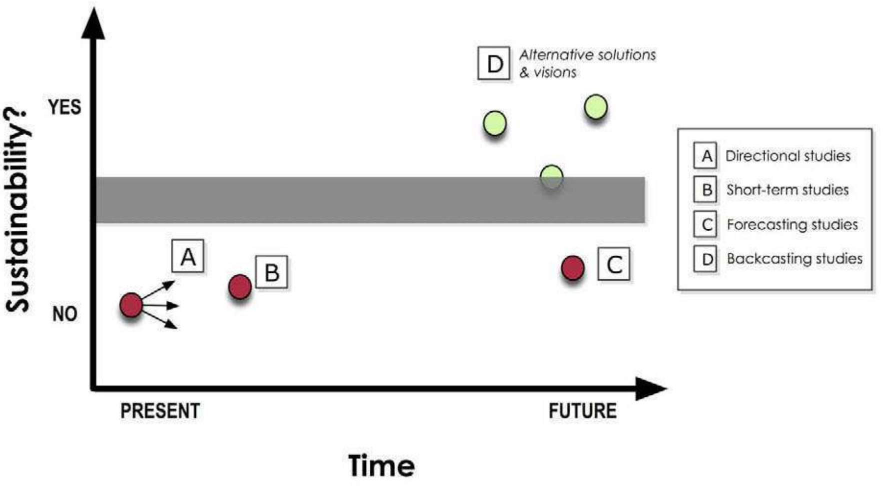

***Figure 3-10**: Application of backcasting to sustainability studies. The conceptual diagram indicates that some studies, such as forecasting or short term studies may not be sufficient or powerful enough to reach a desirable level of sustainability, as they are more appropriate for marginal change, whereas backcasting is useful when extreme or radical change is required. Redrawn from Dreborg (1996).*

This process also allows for the determination of the physical feasibility of the desired future vision and identifies what policy measures would be required to reach that point (Robinson, 1990)[28]. Backcasting is ideal to address complex, long-term, solutions-oriented future studies with a high degree of uncertainty (Robinson, 1990; Dreborg, 1996; Mitchell and White, 2003).

Further, combining qualitative and quantitative scenarios (that is, stories and models) has been used extensively in long-term global studies on energy, climate, water and global change (Mitchell and White, 2003; Pacala and Socolow, 2004; Netherlands Environmental Assessment Agency, 2006; Royal Dutch Shell, 2008).

In order to understand the global implications of peak phosphorus for future food security, a future scenarios analysis was carried out. *Paper IV* presents the entire analysis and findings. The analysis developed qualitative and quantitative scenarios for meeting global phosphorus demand, while accounting for substantial uncertainty about future food demand, lack of consensus about the key issues and limited data regarding the availability of phosphate rock. With this uncertainty in mind, the purposes of the scenarios were, firstly, to allow consistent analysis of a disparate group of options within a single framework (there are currently numerous options under investigation by different groups). Secondly, they were used to determine what possible supply and demand measures could meet future global food demand in the longer term (50-100 years), assuming a peak in phosphate rock production by 2035. Thirdly, they were used to trigger debate among scientists and policy-makers about preferred phosphorus futures, alternative pathways and what is feasible. Finally, they were used to support future decision-making.

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[28] Robinson (1990) provides an outline of the iterative methodology of backcasting.

In line with its orientation towards sustainable futures and its integrative approach, this doctoral study uses scenarios which address not only the business-as-usual case, but also what a more sustainable scenario might look like. For this reason, the future studies approach of 'Probable, Possible, Preferred' futures was applied, following Gidley et al. (2004). A 'probable' scenario considers *where are we heading?* by forecasting business-as-usual. A 'possible' scenario considers *where could we go?* by backcasting from a maximum achievable scenario while a 'preferred' scenario considers *where do we want to go?* (Gidley et al., 2004) by backcasting from a desired future situation taking into consideration sustainability criteria. The preferred future in this case is based on global food security (as defined in section 4.2), since this is considered the greatest global significance of phosphorus resources for humanity, in addition to optimal soil fertility and minimum environmental impacts (Cordell, 2008b)[29].

Again, due to the lack of data, monitoring and research (as described in section 4.5), this analysis is indicative and should be considered for the orders of magnitude and general trends it identifies, rather than for its precision. In this way, they the scenarios developed in this research can be used as a framework to stimulate discussion and further data collection to increase the accuracy of assumptions.

Due to the complexity and infancy of this research field, the scenarios looked at individual supply and demand options, rather than at 'package' socio-political future scenarios (such as a highly globalized, low carbon future), to tease out the possible contributions of individual measures, including:

Demand measures analyzed:

- Changing diets
- Food chain efficiency
- Agricultural efficiency

Supply-side measures analyzed:

- Phosphate rock
- Manure
- Human excreta
- Food waste
- Crop residues
- Other sources (*including ash, bone and animal meal, algae, seaweed and other marine sources*)

The analysis and findings are provided in *Paper IV*. A next step could perhaps develop more integrated socio-political scenarios, as described in section 8.2 on research recommendations. Assumptions and calculations are provided in Appendix A-2.

In addition to the global scale application of future scenarios and backcasting, the principles of backcasting were also used to design and facilitate the stakeholder qualitative visioning exercise in the national stakeholder workshop (Appendix E outlines the workshop design, structure and outcomes).

3.6 Methodology for analysing the 'human activity' system

To analyze the human activity system (including actors, rules, norms, worldviews), the following analyses were undertaken:

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[29] Ideally, this visioning would have engaged international stakeholders again via a workshop, however due to resource constraints, the worldviews drawn from the first interviews and analyzed in *Paper II* and *Paper III* were used.

- Soft systems methodology was used as a structured systemic inquiry to better understand the problem situation, major worldviews and reasons for system failure;
- Semi-structured stakeholder interviews were undertaken and analyzed qualitatively, to elicit stakeholder perspectives; and
- An institutional analysis (specifically drawing from a) Young's 'Lack of Fit' analytical frame b) Vatn's socio-ecological system framework and c) the Earth System Governance program's notion of Architecture).

The literature review revealed a lack of adequate institutional structures designed to govern global phosphorus resources for long-term food security. Few methods or approaches have been developed for the study of global *non*-governance, and indeed Earth System Governance researchers acknowledge there is a lack of research which investigates such instances of 'non-governance'. The approaches outlined below were essentially undertaken iteratively, in parallel, and informed one another.

3.6.1 Soft Systems Methodology

Soft Systems Methodology (SSM) is appropriate for exploring 'messy' problems that are often complex, hard to define, and contain a significant social and political component. Given the complexity of the phosphorus problem situation and the substantial institutional and social barriers to possible solutions, SSM was considered highly appropriate. SSM facilitates a structured, systemic and transdisciplinary inquiry and further is an iterative approach and not intended to be used as a step-by-step methodology.

SSM has its origins in systems engineering, picking up where a purely hard approach failed to address issues that were complex and had a high social and political component, such as power dynamics (Checkland, 2001). While in hard systems thinking, pre-defined objectives are a given, in many 'messy' managerial problems, objectives are not actually known, and hence form part of the problem-solving (Checkland, 1999). In this way, SSM becomes an ongoing learning system, or a process of inquiry (Checkland, 2001). Originally developed as a seven-step process (Checkland, 1999), SSM has now evolved over 30–40 years to become a more dynamic, iterative process of exploring a problem situation using *rich pictures*, *root definitions* of the purposeful activities identified, and developing conceptual models that can be compared to the real world in order to identify feasible and desirable change (figure 3-11) (Checkland, 2001).

Dick and Swepson (1994) aptly describe SSM as essentially consisting of four dialectics: firstly, a dialectic between the 'real world' situation and 'root definition' of a conceptual system relevant to the situation[30]; secondly, between this root definition and a conceptual model of the system developed by the researcher (to ensure the root definition aptly defines the model and vice versa); thirdly, the conceptual model is compared back to the original problem situation, with an intent to identify possible solutions to the problematic situation, followed by a debate to distill differences in *Weltanschauungen*; and finally this debate leads to a plan of action and what is feasible and desirable in reality. These cycles are each iterative processes.

[30] Note, the description of the 'root definition' in *Paper II* also should refer to the conceptual system (that is, it defines the conceptual system, not the 'real-world' situation).

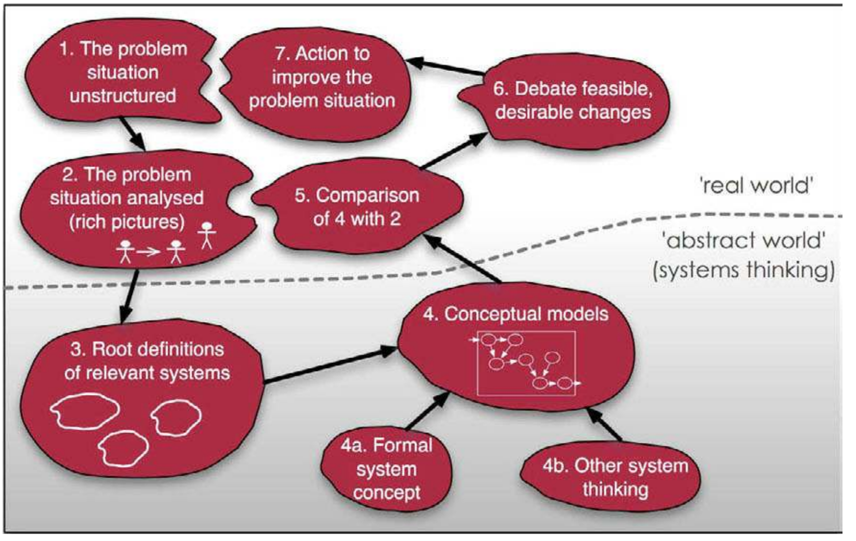

Figure 3-11*: Depiction of the Soft Systems Methodology as a dynamic and deliberative process moving between the 'real world' problem situation and the conceptual or abstract world. Redrawn from Checkland (1999).*

Soft Systems Methodology was applied in this study by firstly conceptualising the current situation through a series of rich pictures (see Appendix C-1), followed by identifying multiple transformations and the worldviews associated with them. For example, 'hungry people' transformed into 'sufficiently fed people', supported by the *Weltanschauung* of global food security. The TWOCAGES[31] mnemonic (Transformation, Weltanschauung, Owner, Customer, Actors, Guardian, Environmental Constraints, System) was used to identify the various actors involved, and the environmental constraints on the system (see Appendix C-2). In order to build a conceptual model of the ideal system, a 'root definition' was developed to capture the essence of the purposeful activity. That is *a system to produce quality phosphorus fertilizer, by sustainable means, in order to meet the fertilizer needs of the world's farmers to feed the world population*. A conceptual model of the human activity required to undertake the tasks in the root definition was developed iteratively. In order to function as a complex system, monitoring, feedback and control loops were required. The conceptual model was then compared to the current situation in order to identify points of current system failure that could be improved. For example, in the real world situation, the feedback loop working to correct the system was at best, very weak. Checkland's criteria of Effectiveness, Efficacy and Efficiency were also extended and used to evaluate the real world situation. The application and findings of the soft systems analysis are detailed in *Paper II*.

The application of Soft Systems Methodology is typically undertaken via ongoing engagement with the stakeholders involved in the system (and the inquiry is often a co-learning process). This high level of stakeholder engagement was not possible beyond the initial stakeholder interviews (and the national workshop, interviews and oral information in the case of the

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[31] TWOCAGES is a variation of Checkland's CATWOE mnemonic (Customer, Actors, Transformation, Weltanschaaung, Owner, Environmental constraints). The TWOCAGES mnemonic was developed by staff at University of Western Sydney due to a belief that clients and students could more easily work with a mnemonic where the 'Transformation' comes first.

Australian case-study).

The soft systems inquiry was used in this doctoral research in a number of different ways throughout the analyses, including:

- Enriching my scientific inquiry through SSM's *systematic* approach (for example in defining boundaries, defining relationships between entities, and identifying the essence of the 'purposeful activity' – that is, determining what the system is trying to achieve);
- Providing an *overarching* framework that contained and connected analyses of both physical and human systems.
- Complementing the overall approach. SSM was undertaken *iteratively* in parallel with other components;
- As a *learning* tool, very much related to the 'finding out' stage (rich pictures aided my ongoing critical literature review trying to make sense of the 'messy' situation);
- Aiding identification of key *stakeholders*, preparation of stakeholder interviews and stakeholder analysis;
- Aiding, identifying and explaining the different *framings* and *worldviews* of the phosphorus problem and the implications for potential solutions (not just by stakeholders interviewed, but in the literature and from informal discussions);
- Aiding the development and refinement of sustainability *criteria* for governing global phosphorus resources (Five E's – Efficiency, Effectiveness, Efficacy, Ethics, Emergence);
- Identification of the lack of effective monitoring and feedback loops to correct the system;
- Enabling *critical reflection*, essential for (transdisciplinary) doctoral research. For example, reflecting on my conscious or subconscious system boundaries: the process highlighted my bias towards human excreta as a physical solution over and above other physical or institutional solutions. SSM forces the analyst to stand outside the context they are submersed in, and then step inside it again. SSM also enabled me to articulate my dynamic participant-observer role in the process.

In this way, the role of SSM in my research can be compared to that of a good mentor: not providing me with the answers, but knowing what questions to ask to facilitate and structure my own critical reflection and analysis.

3.6.2 Semi-structured stakeholder interviews: design and analysis

Given the substantial lack of publicly available data, research, analysis and policy discussion on the long-term future of phosphorus resources for food production (documented in *Paper I* and in chapters 3–5 of this thesis), international stakeholder interviews were undertaken to elicit primary data. According to Boyce and Neale (2006), in-depth interviews is a qualitative social research method that involves "*conducting intensive individual interviews with a small number of respondents to explore their perspectives on a particular idea, program, or situation*" (p.3). The method of in-depth interviews with a small number of respondents was chosen rather than surveys with broad coverage. While a drawback of qualitative analysis of in-depth interviews is that they are time intensive and often involve a small number of respondents, the advantage over surveys (more so with quantitative analysis of surveys) is they enable probing and discussion around issues and perspectives offered by respondents to open-ended questions (Kvale, 2009). This can be highly valuable to the findings and provides substantially more insight and depth into respondent perspectives, particularly when the topic(s) discussed are complex, 'messy' and ill-defined (as is the case with the phosphorus situation).

Whilst conducting and analyzing in-depth interviews is an established and accepted qualitative social research method (Kvale, 2009; Patton, 2002; Legard et al, 2003; Goodrick, 2007), there is often some confusion and misunderstanding by scientists outside the field as to what in-depth interviews are and are not. A common criticism is that the small sample size is neither randomly selected nor statistically significant. In-depth interviews are however not intended to be statistically significant, rather, they often seek the views of specific individuals or groups (Goodman, 2001). In this case, criteria-based purposive sampling was used to identify potential respondents (elaborated below).

The interviews were intended to complement institutional and physical analyses in this research study. The purpose of the stakeholder interviews was firstly to explore how key international stakeholders perceive phosphorus in relation to sustainability and global food security; and secondly to further shed light on why phosphorus security has not been recognized as being critical in the dominant discourses on global food security. Of specific interest was to explore the themes of long-term phosphorus availability and accessibility, views on sources of phosphorus, current and future roles and responsibilities, and possible future trends.

For the purposes of this thesis, stakeholders are distinguished from actors in the following categorical way. Actors are *conceptual* entities defined by certain roles in which they act within a system. For example actors[32] can act as beneficiaries, victims, customers, owners, guardians or observers. Stakeholders are defined as specific *real-world* groups, organisations or significant individuals, within a conceptual actor category. Stakeholders directly or indirectly influence (or are influenced by) the situation or phenomena under investigation. This definition also extends to those who have the *potential* to affect or be affected by the situation (rather than being restricted to those who have an existing relationship), and includes both voluntary and involuntary influences (Grimble and Wellard, 1997). For example, as described in the soft systems analysis in *Paper II*, an actor may be a 'phosphorus producer' (defined by the act of producing), while a specific real-word stakeholder within this actor group is the International Fertilizer Industry Association.

Deciding who is a stakeholder is determined in part by the system boundary (discussed in section 3.2). Criteria-based purposive sampling was undertaken to select appropriate stakeholder organisations for this study. Stakeholders were short-listed if they were:

- An international organisation (for example UN bodies, industry associations, an international research institute);
- actively working on aspects or core sectors related to phosphorus in the global food production and consumption system;
- actors who take the roles of guardian, monitor, producer, user, coordinator, observer (researcher); and
- not primarily involved in eutrophication and water quality issues.

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[32] In some instances, actors can be non-human entities, as defined in Actor Network Theory (ANT). ANT gives equal weight to both inanimate and animate objects, thus bridging the social-technical divide and facilitating the study of the relationships between human and non-human actors among others (Tatnall and Burgess, 2002).

A number of potential stakeholders were shortlisted and assessed in terms of their role, agenda, connections to phosphorus, and other criteria (see Appendix D). Where more than one stakeholder organisation addressing a similar aspect was identified, the stakeholder organisation with the more official status, power, influence or relevance to the specific system under investigation was given higher priority.

This resulted in interviews with international stakeholders representing the aspects of global food security, the environment, the fertilizer industry, geological mineral reserves, sustainable sanitation and public health as depicted in table 3-1 and figure 3-12. The actual roles of each of the six respondents interviewed are depicted in this figure and their conceptual roles are indicated in table 3-1.

Table 3-1: *For each important aspect of phosphorus in the global food system, the actor, conceptual role and stakeholder group interviewed is indicated.*

Aspect related to P in global food system	***Actor group (human or non-human)***	***Role type (related to P)***	***Stakeholder organisation selected***
Global food security	Farmers, hungry people	Guardian (potential); representing users	**FAO**
Fertilizer industry	Fertilizer producers, distributors	Producer	**IFA**
Geological phosphate resources	Phosphate rock	Monitor	**USGS**
Public health	Consumers, 'excretors'	Policy-maker/influencer	**WHO**
Environment	Environment and food system	Policy-maker/influencer	**UNEP**
Sustainable sanitation	'End-of-life' nutrients (sanitation)	Research-practitioner	**SEI**

[Note: FAO = Food and Agricultural Organisation of the UN; IFA = International Fertilizer Industry Association; USGS = US Geological Survey; WHO = World Health Organisation; UNEP = United Nations Environment Programme, SEI = Stockholm Environment Institute]

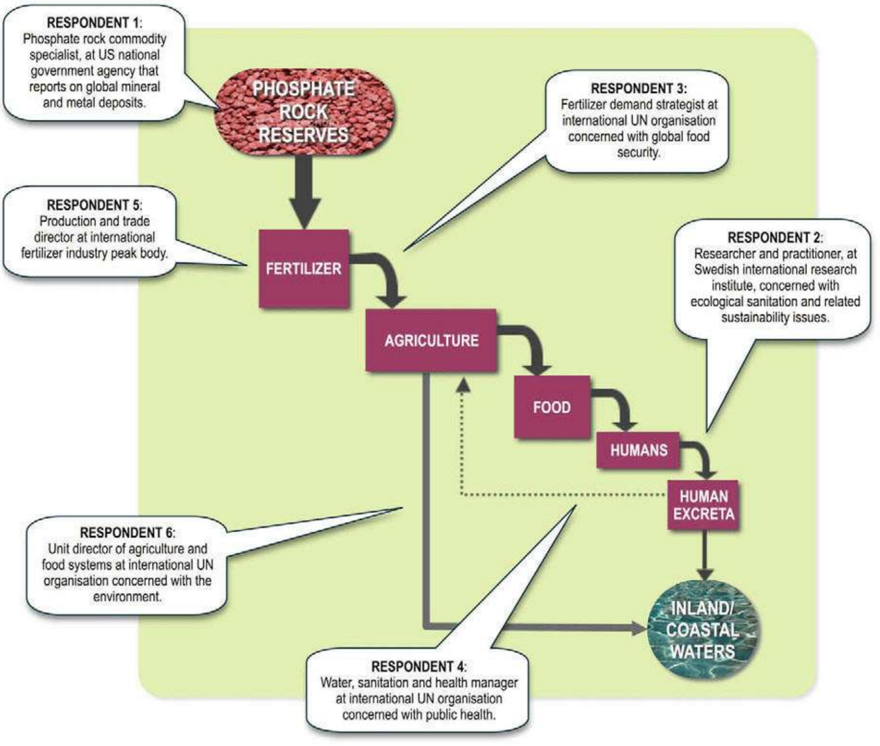

Figure 3-12*: Description and positions of respondents interviewed and their stakeholder organisation associated with different aspects of the physical flows of phosphorus through the global food production and consumption system. Source: created for this research.*

All six respondents were actively engaged in the global phosphorus food system in some way and were in important roles where no others were working. For example, Respondent 1 is the official monitor and producer of publicly available global data on phosphate rock. Respondent 5 represents the majority of the world's phosphate fertilizer producers, while Respondent 3's organisation is an official (UN) guardian for global food security. Further, Respondent 3 was the only individual in the entire stakeholder organisation responsible for farmers' fertilizer demand. While there are numerous organisations at the international level related to food security (such as IFPRI, IAASTD, CGIAR, GECAFS), FAO is perhaps more influential in terms of policy, or at least has a more official or formal responsibility. At the time of the interviews, recovery and re-use of phosphorus from excreta was a main focus of this research, and only later was the role of excreta toned down and integrated with other important potential areas of change (such as diet and agricultural efficiency). Other stakeholders that could have been interviewed include the WTO regarding trade in phosphate, however the importance of the market system in governing phosphorus was only clarified after the interviews.

The appropriate individual within each stakeholder organisation was identified via a) a literature review (including key stakeholder reports), and b) assessing department organisational charts and position titles. Heads of departments were prioritized due to their authority and seniority. It is important to note that whilst the views quoted in *Paper III* are those of individuals within an organisation, their formal roles and key responsibilities within those organisations mean their views impact on the outcomes of their organisation.

Once all appropriate stakeholders and specific individuals were identified, respondents were initially sent a letter inviting them to participate in the study, with a consent form attached (see letter in Appendix B-1). The invitation clearly stated that the topic was to explore the sustainability of global phosphorus resources in the context of global food security. Follow-up phone calls or emails answered any concerns or questions of respondents and secured a time for the interview. All stakeholders agreed to participate in the interviews, or to have a colleague participate instead as they saw appropriate.

Semi-structured stakeholder interviews are useful for yielding unpublished information and the views, assumptions and perspectives of key stakeholders. In-depth interviews rather than the use of a fixed questionnaire enabled probing and exploration of the issues in more breadth and depth. Undertaking the interviews 'face-to-face' can facilitate trust and relationship building in addition to the observation of non-verbal cues. Such semi-structured stakeholder interviews differ from statistically significant samples in that they do not aim to represent a population. Rather, in-depth stakeholder interviews are designed to elicit the views of key individuals.

The interviews were undertaken in September and October 2007, prior to the height of the global food crisis, and the soaring prices of phosphate rock. The interviews were conducted face-to-face at or near the respondents' workplaces in Europe[33]. During the one-hour interviews[34], respondents were asked a range of open-ended questions (see Appendix B-2) followed by probing follow-up questions. The consent form was discussed and signed at the end of each interview.

Immediately following each interview, two to three pages of reflexive field notes were taken (they included such things as documenting non-verbal observations, how I may have influenced the interview in any way, how I felt at the time – see Appendix B-3). Interviews were digitally recorded and transcribed. Following transcription of 80–90% of the recordings and write-up of notes, respondents were sent quotes from the interview that I was considering using in the analysis and write up. The partially transcribed interviews, reflexive notes and observations resulted in 61 pages of text.

Interview data, reflexive field notes and memos were analyzed qualitatively taking a hybrid approach. The data was analyzed qualitatively because the issues involved related to institutional perceptions, which are more readily qualified rather than quantified. The inductive analysis drew from grounded theory. Sociologists Barney Glaser and Anselm Strauss developed grounded theory in 1967 as a structured methodology which allowed theory to emerge from data (Goodrick, 2007)[35]. Grounded theory was selected as a highly appropriate methodology to address those of my research questions with little-known answers, such as *why* phosphorus might not be perceived as critical in the food security debate. Taking a purely

[33] With the exception of the interview with the world phosphate rock expert, which was conducted as a telephone interview due to travel distance.

[34] Some interviews lasted longer than one hour with the respondents' approval.

[35] However a disagreement about key aspects (e.g. the coding paradigm) of their theory soon after, led to the divergence of the two researchers and consequently two schools of grounded theory have since developed (Goodrick, 2007). The Glaser school claims to maintain the 'traditional' grounded theory approach, which takes a more subjective and hence fluid approach, while Strauss and colleague Corbin take a more objectivist and structured approach.

deductive approach to answer this question would have limited the research findings. Whilst the grounded theory researcher should be careful not to enter the analysis with preconceived theories, both main schools of grounded theory maintain to a greater or lesser extent that literature and experience can be gainfully used to enhance the analysis (Strauss and Corbin, 1998). Constant comparison is a key feature, where the grounded theory researcher literally 'flip-flops' (Goodrick, 2007) back and forth between data sources (for example by comparing one interview transcript to another interview transcript), looking for emerging theory to explain the research questions. Furthermore, since 'all is data' according to one of grounded theory's founders (Glaser, 1998), grounded theory allows data from multiple sources to be analyzed in the same framework.

These datasets were highlighted based on the following criteria: interesting, relevant to research questions, revealing, unique. Highlights were then coded and themed. Emerging themes were developed from the data to address the question of why phosphorus scarcity is not being addressed in international discussions on global food security. A stakeholder response matrix was also developed to aid thematic analysis by constant comparison between respondents in relation to certain themes (see Appendix B-4). Constant comparison, re-reading of transcripts and listening to audio recordings ensured emerging themes or concepts were not lost.

The respondents' perspectives exist against a backdrop of institutional arrangements and conventions at that given point in time. In line with Strauss and Corbin (1998) and Glaser's notion that "all is data" (Glaser, 1998), literature, observations and media were productively used. Therefore, both official documents of the respondents' organisation and other informative texts (such as institutional websites and keynote speeches at international conferences) were used to enhance the analysis and have been referenced accordingly. Finally, to capture the nature of rapid changes that occurred immediately following the interviews, media texts and the aforementioned informative texts were also drawn upon.

Following Kvale (2009), ethical issues associated with the interview process and use of data were addressed at all key stages of the research. For example, academic research ethics approval was obtained prior to undertaking the study and consent forms were signed by respondents following each interview. During the sampling and interviewing phase, there was no claim that I was entering the research field completely neutral. As described by Patton (2002) such claims to objectivity can be regarded as unrealistic: "*Distance does not guarantee objectivity; it merely guarantees distance*". Rather, the aim was to maintain 'empathic neutrality' with participants and the analysis. My values (as declared in chapter 2) are based broadly on the principles of sustainable development, the laws of thermodynamics, livelihood security and the human right to food.

3.6.3 Institutional analysis: Young's 'Lack of Fit' framework and Vatn's social-ecological framework

The use of soft systems methodology and the investigation of stakeholder perspectives to analyze the human-activity system as described above, were complemented by an analysis[36] of the institutional structures. Actors are inherently embedded within an institutional system which is also of importance, because actors form institutions, and institutions form actors (Vatn, 2005). Institutions are defined broadly here as:

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[36] This was more minor relative to the other analyses.

> *the conventions, norms and formally sanctioned rules of a society. They provide expectations, stability and meaning essential to human existence and coordination. Institutions regularize life, support values and produce and protect interests* (Vatn, 2005, p.60).

This analysis specifically involved the application of Young's 'Lack of Fit' framework and Vatn's Social-ecological framework.

Young's 'Lack of Fit' analytical frame was applied (Young, 2002; Young, 2005) to broadly guide the investigation of the dynamics between the physical system and the institutional arrangements pertaining to that system. Lack of Fit, together with Scale and Interplay were the three central analytical themes of the Institutional Dimensions of Global Environmental Change program (IDGEC) to address institutional aspects of sustainability problems, such as design and effectiveness of institutions. 'Lack of fit' refers to a misfit between a natural cycle and the institutional arrangements around that cycle. Young contends that:

> *the capacity of these [institutional] arrangements to prevent undesirable environmental changes and to solve environmental problems once they arise is determined in considerable measure by the degree to which they are compatible with the biogeophysical systems with which they interact*" (2002, p.1).

Misfit can therefore be the cause of ineffective governance. This analytical frame was considered highly appropriate because it enabled an analysis of the interconnections between the physical and human-activity systems, and was consistent was the systemic approach taken in this doctoral study. For example, consistent with critical systems thinking, Young stresses the importance of boundaries and what is included and excluded from a resource regime: "*a regime that ignores what turn out to be significant elements of an ecosystem cannot produce sustainable results*" (2002, p.12). He further suggests that even when a resource regime is explicitly designed to cover the natural system, the state of that system can change, and therefore if the regime does not have the capacity to adapt to the changed boundaries of the natural system, then misfit will occur.

Vatn's social-ecological framework (Vatn, 2005) was modified and applied to analyze the institutions and actors engaging in the resource use activity. This framework involves an analysis of the dynamics of: the attributes of the resource, how this relates to technology, the institutions and actors/agents present, and importantly, the action arena where they interact and the outcome and feedback loops for the status of the resource (depicted in figure 5-15). This high-level framework was considered appropriate for analysing the phosphorus problem situation, firstly because it allows a systematic analysis at the scale of this research (that is, on the international level)[37]. Secondly, this framework allows for a transdisciplinary approach that addresses the interplay between the institutions and attributes of the resource. While the Vatn framework was implicitly developed to analyze and manage *local* and *renewable* resources (such as common pool resources), in this thesis it has been applied to the governance of *global non-renewable* resources. The key modifications include shifting 'patterns of interaction' from the physical realm between agent choices and outcomes, to the patterns of interaction in the social space occurring between 'Agents' and 'Institutions'. This has been renamed the 'Action Arena' after Ostrom (2006). The action arena is the space where issues are discussed and negotiated, goods are exchanged and decisions are made. Outcomes from the action arena are highly influenced by powerful agents. Therefore a final modification was to make explicit those agents with a high degree of power (see stakeholder analysis in Appendix D-2). As noted by Young (2007), a key feature that distinguishes the problem at the local versus global scale is that the

[37] This is not to say other scales are not important. Indeed, multi-level analyzes are important for addressing system failure even at the global level (Ostrom, 2006), however this has been outside the scope of this research. A national case study was however undertaken (i.e. *Paper V*).

appropriators and managers tend to be the same actors at the local level, but not at the global level. In the case of phosphorus, the appropriators are firms and nation states, whereas the managers are international organisations (see section 5.5 for further explanation and application).

To a lesser extent, the analysis was also influenced by the principles and problem framings of the *Earth System Governance* project (ESG) (Biermann et al., 2009) and Art's notion of *Discursive Institutionalism* to articulate the rapid changes occurring in this field (Arts and Buizer, 2008). The ESG project proposes five analytical problems – the "five A's" of Architecture, Agency, Adaptation, Accountability and Allocation – to address the core question of "*how integrated systems of governance can support a co-evolution of nature and human societies that leads towards sustainable development*" (Biermann et al., 2009, p.14). While institutional *architecture* addresses the design and effectiveness of multi-level network of formal and informal structures governing the earth system, *agency* focuses on the actors involved in the formation and steering of these structures. The importance of flexible governance systems capable of responding to short- and long-term dynamic changes in social-ecological systems is captured by the problem of *Adaptation*. *Accountability* of agents and structures extends beyond the nation state to the increasing proliferation of the private sector as a key agent in the governance of earth systems. *Allocation* addresses the problem of both equitable distribution of resources and the access to those resources. The five A's have influenced the analyses and problem framing in this research in various ways, ranging from addressing accountability in relation to data scarcity (section 3.4.2 and the research recommendation 2 in chapter 8), to enhancing the analysis of both the current institutions governing phosphorus and the effectiveness of those structures in section 5.5.

In his articulation of *Discursive Institutionalism* (Arts and Buizer, 2008), Arts suggests that discursive shifts can occur either through incremental change or rapid change such as 'shock events' (and indeed the framing of those shock events) (Wiering and Arts, 2006; Arts and Buizer, 2008). However Arts's notion of discursive institutionalism further implies that while a discursive shift may be evident, 'deep' or significant institutional change only occurs when there are resultant effects on policy arrangements, that is, shifts in the actors, power and rules.

The application of these approaches and their findings is described in detail in section 5.5 and in *Papers II* and *III*.

3.7 National case study

The main objective of the national case study was to determine the implications of the global phosphorus problem situation for a national food production system. According to Zurek and Henrichs (Zurek and Henrichs, 2007), the findings from global scenarios or assessments cannot always be directly transferred to the national or lower geographical levels. The relationship between the global phosphorus analysis in this doctoral research and lower geographical scale analyses would be considered 'coherent' according Zurek and Henrichs classifications of the interconnections between scenarios at different scales. Coherent scenarios "*follow the same paradigm or are different representation of the same scenario archetype — in other words the scenario logics 'match'*" (Zurek and Henrichs, 2007, p.1289). As noted in section 5.2.3, substantial environmental and socio-economic variability in the nature of the phosphorus-food dynamics exists between different regions. Further, due to this variability, it was not assumed that the findings from the national case study would be applicable to other countries, however some insights and the analytical frameworks were perhaps transferrable. Australia was selected because a) it was a net food-producing nation and therefore was of global significance, b) financial and administrative resources in addition to networks were accessible.

While the global-scale *findings* could not necessarily be scaled down to the national level, many of the methodologies and methods employed to investigate the global situation (presented in sections 3.5-3.6), were applicable on multi-scales, and hence used in the national case study. Due to the substantial lack of data at the national level (similar to the international level as outlined in 3.4.2), multiple sources of primary and secondary data were sought. This included:

- Literature (including peer-reviewed academic papers, industry and government reports, other research reports, media);
- Two semi-structured in-depth interviews with the national association representing the fertilizer industry and the governmental department monitoring Australia's mineral resources (other key stakeholder representatives – including the national association representing farmers - were invited to participate in the interviews but declined);
- Oral information from other stakeholders (such as the Organic Federation of Australia to determine usage patterns, challenges and opportunities related to the use of manure and other organic sources of phosphorus); and
- National stakeholder workshop to collect both individual and collective perspectives on phosphorus (described in detail in Appendix E-1).

The analysis for the case study involved a combination of qualitative and quantitative approaches, including:

- Soft Systems inquiry (particularly through the use of rich pictures) to guide both understanding of the current situation and identify relevant stakeholders;
- Australian substance flows analysis of major phosphorus flows through the Australian food production and consumption system;
- Literature review of Australia's historical and current relationship with phosphorus in food production; and
- Stakeholder deliberation on pertinent issues and preferred sustainable phosphorus pathways based on participatory backcasting methodology at the national stakeholder workshop.

The outcomes of the Australian case study also contributed to multiple outcome spaces (as discussed in chapter 7). This included:

- Peer-reviewed knowledge: *Paper V*
- Situation/context & mutual learning:
    - Research discussion paper prepared for Workshop (Cordell and White, 2008);
    - Synthesis paper from Workshop (Cordell and White, 2009);
    - Network development;
    - Invited presentation at the Australian Fertilizer Briefing (national industry conference) (White and Cordell, 2009);
    - *UTSpeaks* public lecture (to audience of 450 people) (Cordell, 2009b);
    - Media - paper, radio, TV (for example: ABC Radio National, 2008; Warren, 2008; ABC Fora, 2009); and
    - Professional publications – government, industry, interest groups (for example: NSW Department of Primary Industries, 2008; CHOICE Magazine, 2009;

Cordell, 2009a; Cummins, 2009).

While this chapter has justified, conceptualized and described the theoretical and methodological framework (including methods) used in this doctoral study, Chapter 7 then revisits the arguments made for transdisciplinary research and reflects on the intentions of science in relation to transdisciplinarity.

CHAPTER 4: THREE GLOBAL CHALLENGES: ENVIRONMENTAL CHANGE, FOOD SECURITY AND RESOURCES SCARCITY

This chapter provides important contextual background to the central argument of this thesis. That is, it both puts phosphorus scarcity in a wider global sustainability context, and, initiates the central argument by demonstrating how phosphorus is missing from these important global sustainability discourses. For readers unfamiliar with the significance of phosphorus for food production, sections 5.1, 5.2 and *Paper I* provide explanation and analysis. This chapter reviews, analyzes and critiques the relevant body of literature related to global phosphorus scarcity in the context of food security and environmental change. Some researchers and practitioners in other fields, such as the sanitation sector, have recognised or acknowledged that the finite nature of phosphorus resources (in addition to phosphorus pollution), are important reasons to recover phosphorus from excreta. However, discussion has been limited because a) this has to date had very little connection with food production and food security, and b) it is only a minority of researchers and practitioners within the sanitation sector that have this awareness (as discussed in section 5. 4)

While the framing of these global discourses on food security, environmental change and resource scarcity and their assessments have substantially improved over recent decades through new data and new system insights, phosphorus scarcity is still largely missing. This chapter demonstrates a critical gap, that is, the lack of attention to the importance of global phosphorus scarcity with specific reference to the imminent threat it poses to future food production. This is done by critically reviewing the three fields outlined in figure 4-1, including: 1. (briefly) the relatively new discourse on **global environmental change**, 2. the key discourses of **food security** (including food availability, food accessibility and food utilization); and 3. the conceptualization of **resource scarcity**, with a special focus on a) peak theory, b) oil, c) water and d) non-renewable versus renewable resources in general.

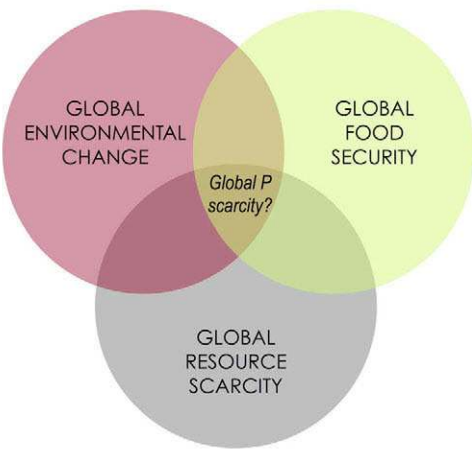

***Figure 4-1**: Three global challenges that phosphorus scarcity directly relates to: global environmental change, global food security and global resource scarcity. Source: created for this research.*

4.1 An unprecedented era of global environmental change

There is little doubt today that the earth is experiencing unprecedented global changes due to human activity (Steffen et al., 2004; WWF, 2004; IPCC, 2007; World Watch Institute, 2008; Biermann et al., 2009; Folke and Rockström, 2009). Key developments over the past decade or so that have increased this understanding include:

1. **The Anthropocene Era**[38]: Human impact on the earth has now surpassed natural variation in many instances (for example, nitrogen fluxes in the environment are double that of the natural biogeochemical cycles) (Steffen et al., 2004). Partly driven by exponential population growth and technological developments since the industrial revolution, human impact has accelerated dramatically in the last 50 years (figure 4-2). The global population is expected to reach 9 billion by 2050 and our impact is likely to increase (UN, 2007).

2. **The Earth System**: The conceptualization of the earth as a system where all components are directly or indirectly connected, such as in the terms/concepts 'Spaceship Earth' (Boulding, 1966), 'The Earth Enterprise' (Pick, 2008) has been around since the Apollo spaceship sent pictures down to the world of planet earth embedded in the black universe. However a substantial shift in this understanding of the earth as a system was enabled by improved global data collection and modelling capabilities, such as data yielded from the Vostok ice core (Steffen et al., 2004) and global assessments such as the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005b). The study of the Earth System was formalized in the Amsterdam Declaration on Global Change (Moore III et al., 2001) which led to the development of the Earth System Science Partnership (ESSP, online) (discussed further below).

3. **Global Change, not Climate Change**: The same Declaration acknowledged that we are in an era of global change, not simply climate change. And the change is characterized by complex interactions between natural and human systems at different scales of time and space (such as within and between cities, agriculture, water and energy). Similarly, others argue there is a need to look beyond carbon and energy to other resource issues (discussed further in section 4.3 on global resource scarcity).

4. **Multiple steady-states**: Although ignored for decades by the mainstream ecology movement, groundbreaking research by Holling (1973) demonstrated that ecological systems do not fluctuate around a single steady state, but rather, multiple steady states. This has significant implications for our understanding of the resilience of natural systems, the human impact on natural systems and in turn for how we attempt to manage those systems. An important example here is that we have the capacity to push a complex natural system past a threshold or 'tipping point' into another, irreversible state (Folke, 2006)[39]. The concept of resilience has now been institutionalized in many forms, perhaps most notably the Resilience Alliance (www.resaliance.org) as described further below.

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[38] This term was coined by 1995 Nobel Prize winner in Chemistry Paul Crutzen (Crutzen, 2002). The related term 'the Anthroposphere' (the sphere of human activity) was earlier referred to by Brunner and Baccini (1991) in their seminal book on material flows analysis entitled 'Metabolism of the Anthroposphere'.

[39] An obvious and straightforward example of *irreversibility* is the extinction of a species.

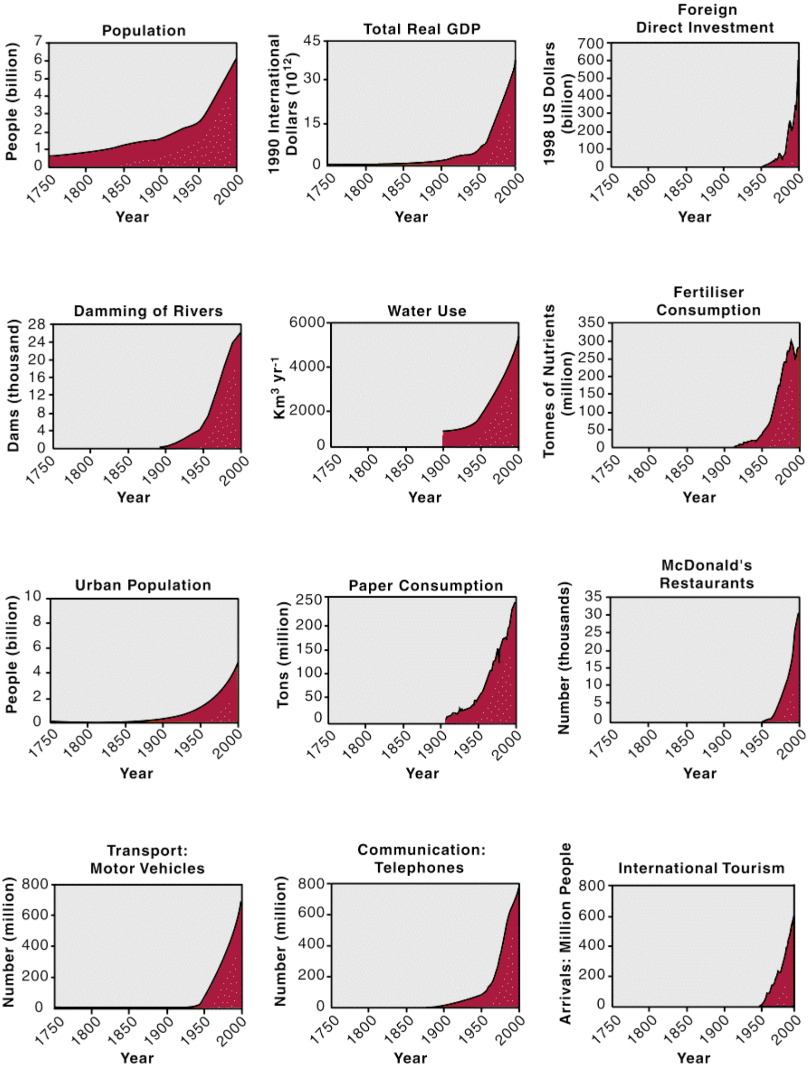

***Figure 4-2**: "The Great Acceleration of the Human Enterprise": indicators of the exponential growth of human activity particularly since the post-World War II period. Source: Steffen et al (2004)*

Instrumental in these new framings has been the undertaking of the Millennium Ecosystem Assessment between 2001 and 2005 which aimed to:

> *assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being* (Millennium Ecosystem Assessment, 2005b, pV).

The Millennium Ecosystem Assessment globally connected environmental change and human impact (figure 4-3). It showed in an integrated way how vital constituents of human wellbeing are dependent on and affected by life on earth, that is, by the 'ecosystem services' supporting humanity. Equally important perhaps was the development of new interdisciplinary international research networks and programs. One notable example is the Earth System Science Partnership (ESSP) which facilitates "*an integrated study of the Earth System, the ways that it is changing, and the implications for global and regional sustainability*" (ESSP, online)[40]. The ESSP defines the earth system as being made up of physical, chemical, biological and social elements, the dynamic connections between these elements, and the outcomes of these dynamics on biota, humanity and other planetary components.

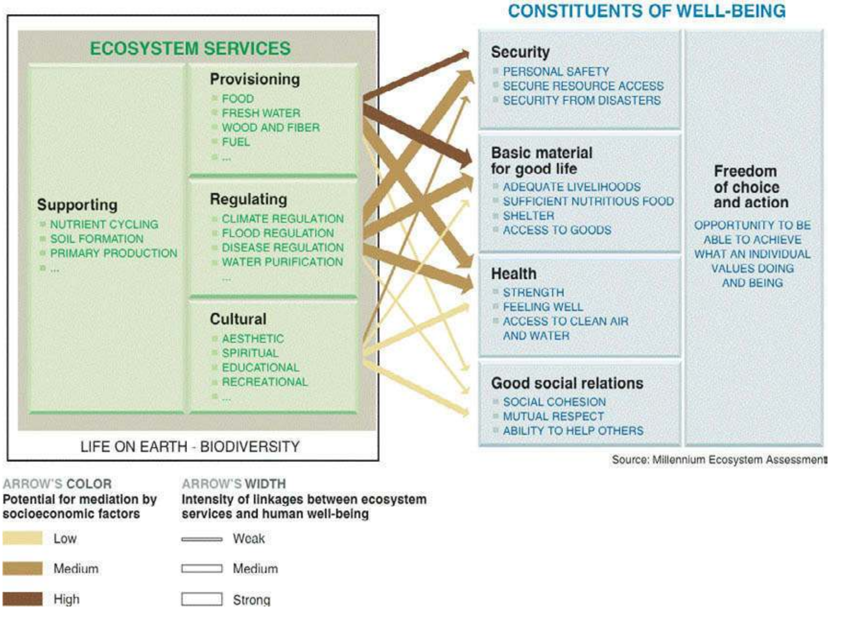

***Figure 4-3**: The Millennium Ecosystem Assessment's conceptualization of ecosystem services supporting fundamentals of human wellbeing. Source: Millennium Ecosystem Assessment (2005b).*

Another related research network is centered around the theme of resilience[41] which addresses the core concepts of resilience, adaptability and transformability. Resilience refers generally to the ability of a system to absorb shocks, adapt or transform in the face of change. While originally developed with reference to predator-prey population dynamics in ecological systems by C.S Holling (1973), resilience concepts have now been applied to social systems. However as Folke (2006) stresses, social systems are fundamentally dependent on and linked to ecological systems and hence it is more constructive to study social-ecological systems with equal attention

[40] The ESSP is the culmination of four programs on global environmental change research: 1. DIVERSITAS (Biodiversity); 2. IGBP (International Geosphere-Biosphere Programme); 3. IHDP (International Human Dimensions Programme on Global Environmental Change); and 4. WCRP (World Climate Research Programme). These four programs are united by four cross-cutting joint projects: Food, Water, Carbon and Human health.

[41] For example, see the Resilience Alliance (www.resalliance.org)

to both fundamental components. Of interest here is not just how social-ecological systems can *persist* or *adapt* through collective action in the face of change, but also the capacity of people to *transform* and create *new* systems when the existing ones are no longer workable or sustainable (Rockström, 2008). More specifically then, the resilience of a system (be it ecological or social-ecological) can be defined by three attributes:

> 1. "*the amount of change the system can undergo and still retain the same controls on function and structure*"; 2. "*the degree to which the system is capable of self-organization*"; and 3. "*the ability to build and increase the capacity for learning and adaptation* (Resilience Alliance, 2009).

In an era of significant uncertainty and surprise (regarding the consequences of climate change, biodiversity loss and other global environmental changes), designing social-ecological systems that are resilient will produce systems that are more likely to be flexible and able to develop and evolve without severe consequences in the long-term. On the other hand, in a system with low resilience (or high vulnerability), even a small disturbance can have catastrophic consequences for humans and ecosystems (Folke, 2006; Folke and Rockström, 2009).

The global discourses described above all have systems thinking at their core (for example, the "Earth System" (ESSP, online), "social-ecological systems" (Folke, 2006), and "food systems" (GECAFS, 2006)). This facilitates the analysis of interlinkages between elements of the system, and the system's relationship to the larger system it is embedded within. Despite this systems approach, none of these frameworks has yet referred specifically to the implications of global phosphorus scarcity for future food production as an important global environmental change concern (as put forward in *Paper I, IV* and indeed this entire thesis). Their conceptual frameworks do acknowledge 'nutrient cycles' as life-supporting ecosystem services or 'fertilizer use' as drivers of change, but all detailed analysis has to date referred to pollution aspects (eutrophication and more recently greenhouse gas emissions) largely attributed to increasing nitrogen and carbon fluxes due to land use changes, fertilizer use and energy consumption (Steffen et al., 2004; Millennium Ecosystem Assessment, 2005b; GECAFS, 2006). For example, the Millennium Ecosystem Assessment chapter on *Food* (chapter 8), mentions 'fertilizer' 10 times, 'nitrogen' seven times, and 'phosphorus' not once. Where the phosphorus cycle is explicitly discussed, such as in the chapter "*The Phosphorus Cycle*" (Millennium Ecosystem Assessment, 2005a, p.341), concern regarding human impact is only raised with respect to eutrophication.

The consequences of ignoring phosphorus in these key integrated models of the earth system that are used as the basis of further research and policy recommendations, are exemplified by the absence of phosphorus in the *Integrated Model to Assess the Global Environment (*IMAGE) 2.4 version (figure 4-4). With regard to this figure, if phosphorus is not included in the Earth System as one of the key biogeochemical cycles (next to Nitrogen, Carbon and Water), then there will be no phosphorus-related global impacts identified to feed in to the policy options. That is, if such models contain no causal links between the phosphorus cycle and global environmental change or the food system, then no policy implications can be drawn, and hence no investment in future research and further investigation into the phosphorus problem. It becomes a self-reinforcing vicious cycle[42].

[42] This is not to say these models cannot change. Indeed, the IMAGE Framework is updated at regular intervals and it is recommended in this thesis that phosphorus scarcity is added to such frameworks.

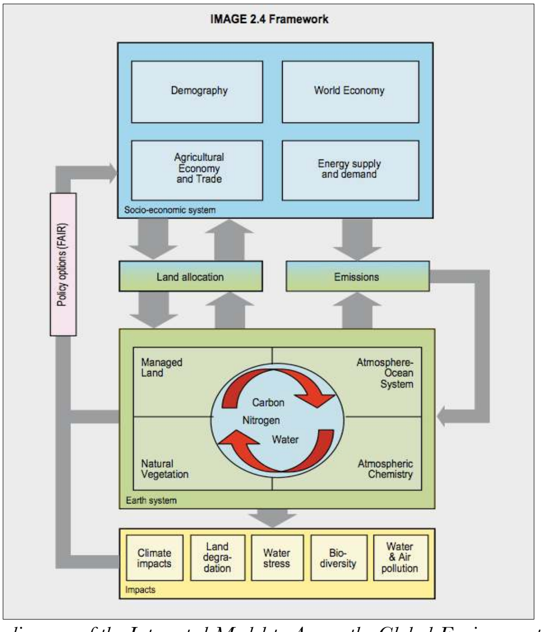

Figure 4-4*: Schematic diagram of the Integrated Model to Assess the Global Environment (IMAGE) version 2.4, indicating the absence of phosphorus next to carbon, nitrogen and water. Source: Netherlands Environmental Assessment Agency (2006).*

Similarly, the recent frame of 'planetary boundaries' by scientists at the Stockholm Resilience Centre provides a very useful framework for conceptualising and assessing important biophysical thresholds (figure 4-5). This builds on previous work on limits and carrying capacity (such as Limits to Growth described in section 4.3). While the phosphorus biogeochemical cycle (together with the nitrogen cycle) is one of nine planetary boundaries considered of global significance to humanity, the parameter used to determine the crucial limit is only "*quantity of P flowing into the oceans*" (2009a, 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). This presents both a concern and an opportunity. It is concerning because according to the analysis, phosphorus cycle is within safe limits, and indeed, the authors suggest it would likely take 1000's years for the phosphorus cycle to exceed this limit[43], based on fluxes to the oceans (Rockström et al., 2009b). The opportunity, is that phosphorus scarcity and implications for humanity could in future revisions be included in such important analytical frameworks.

[43] However due to the uncertainty around the threshold, the safe limit recommended is more conservative.

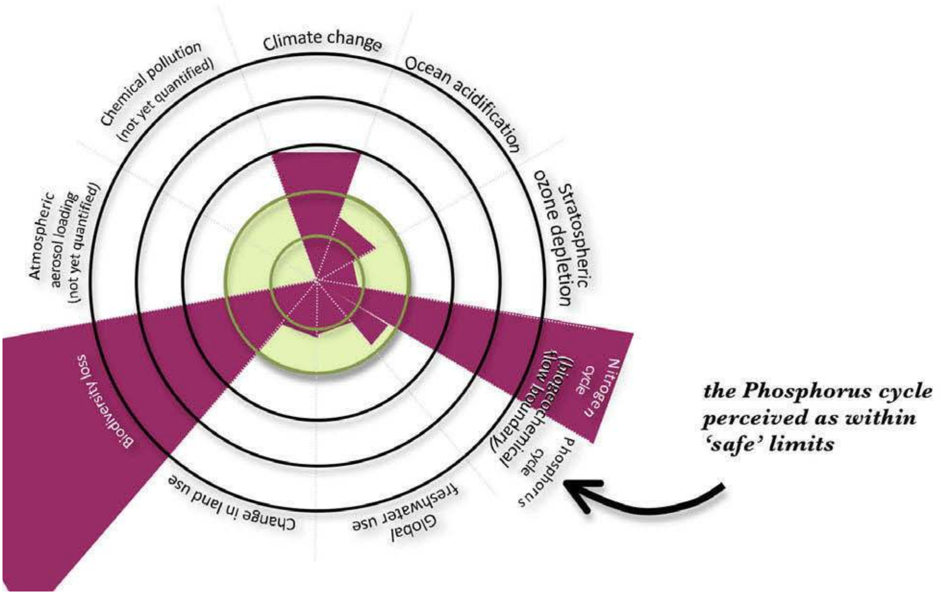

***Figure 4-5**: 'Safe operating space' for nine planetary systems, indicating that the nitrogen cycle, climate change and biodiversity loss have exceeded the safe limit, while the phosphorus cycle is within safe limits. Source: Redrawn from Rockström et al (2009a). [arrow and black text outside original figure are own additions]*

Despite this current failure to recognize phosphorus scarcity, these research programs and frameworks are highly relevant conceptual 'homes' for the phosphorus scarcity discourse. For example, the ESSP's Global Environmental Change and Food Systems (GECAFS) program, self-described as: "*a comprehensive programme of interdisciplinary research focused on understanding the links between food security and global environmental change*" (GECAFS, 2006) is seemingly a highly relevant forum for discussing the phosphorus problem linked with food security[44], however phosphorus scarcity is not currently recognized within it (see more on GECAFS in chapter 4.2).

4.2 Dominant discourses on global food security

Feeding humanity is a serious global issue both today and for the future. Global food security is now considered a global priority (UN, 2000; IFPRI, 2002b). The UN's Food and Agricultural Organization (FAO) states that food security "*exists when all people, at all times, have access to sufficient, safe and nutritious food to meet their dietary needs for an active and healthy life*" (FAO, 2005b, p.1). Yet today, an unprecedented 1.02 billion people are hungry – one sixth of all humanity (FAO, 2009).

Food security is a challenge that can only be met by addressing a number of relevant issues. The FAO's annual State of Food Insecurity (SOFI) reports, the International Food Policy Research Institute's (IFPRI) reports and the UN Millennium Development Project all stress

[44] This view was supported by the then Director of the Institutional Dimensions of Global Environmental Change program in an in-depth private discussion in June 2007.

that food insecurity is a consequence of numerous linked social, economic and environmental factors, including frequent illness, poor sanitation, limited access to safe water and lack of purchasing power (Braun et al., 2004; FAO, 2004; UN Millennium Project, 2005). The Director of the International Assessment of Agricultural Science and Technology for Development (IAASTD), Bob Watson, reiterated the multiple challenges at the launch of the IAASTD report in 2008:

> *We need to double food production in the next 25–50 years, but we also need to make it more nutritious, and affordable for the consumer, and, make sure that the farmer makes a profit. We therefore have 3 goals – we need to feed the world, enhance rural livelihoods where most of the poor live, …and we need to stimulate economic growth. At the same time, need to meet food safety standards…*(Watson, 2008).

More than half the world's population is now living in urban areas and this trend is set to continue (Sanchez-Rodriguez et al., 2005). The estimated 2 billion new mouths to feed by 2025 will almost exclusively reside in the urban centres of developing countries (UN-HABITAT, 2003). Innovative ways to meet the food requirements of the undernourished urban population (particularly those living in peri-urban areas of mega-cities) will be critical to reaching the Millennium Development Goals of eradicating hunger and poverty.

These interrelated challenges can be categorized as three dominant themes in food security: 1. food availability, 2. food accessibility and 3. nutritional uptake (or 'utilisation') (Ericksen, 2008), conceptualized in figure 4-6. That is, food security cannot be achieved (whether on an individual, household or national scale) unless sufficient food can be produced (which relies on both natural and human resources), food can be accessed by households and people have healthy bodies to effectively utilize the nutritional value of the food. While the environmental challenges associated with water, energy and nitrogen resources are acknowledged as critical in the food availability discourse, phosphorus scarcity is absent.

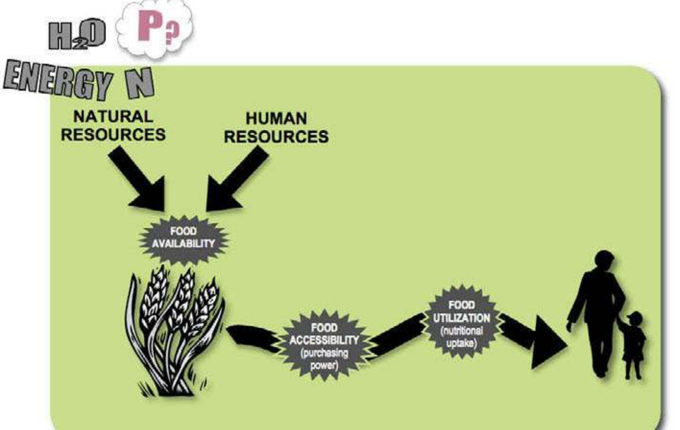

***Figure 4-6**: Three dominant discourses on global food security: food availability (including energy and water scarcity discourses), food accessibility and food utilisation. Phosphorus scarcity is currently missing from the food availability discourse. Source: created for this research.*

Food *availability* has been a key discourse within food security at least since the Green Revolution in the 1960s (IFPRI, 2002a). Historically, crop production relied on natural levels of nutrients and water in the soil and atmosphere and manual or animal labor. Crop yields were relatively low compared to today, limited by multiple factors such as lack of water or poor soil structure as outlined in figure 4-7. To keep up with population growth, increasing famines and changing demographics, external inputs of irrigation water, nutrients, pesticides, herbicides, mechanical rather than manual labor and modification of crop varieties were made (Fresco, 2009). The abundance of cheap energy from fossil fuel sources made the intensification of agriculture and the Green Revolution possible (Pfeiffer, 2006). Today, modern agriculture is dependent on very high and ongoing resource inputs to maintain high crop yields.

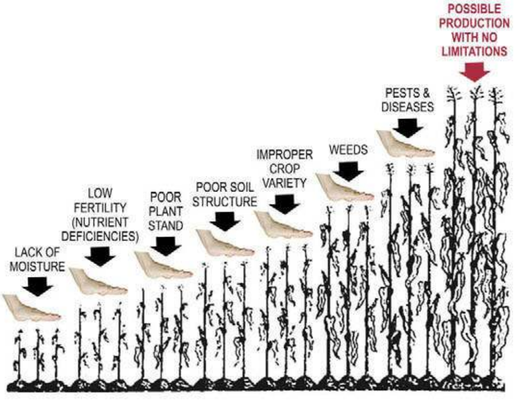

Figure 4-7*: Factors limiting crop yields. Source: redrawn from FAO (2006, fig 10).*

According to many of the key institutions and assessments on food security, global food production will need to double in the coming decades to meet the global demand (Fresco, 2003; IAASTD, 2008; Fresco, 2009). Fresco (Fresco, 2009) and indeed other researchers (Steen, 1998; Smil, 2000a; WWF, 2004; Pfeiffer, 2006; Fraiture, 2007; Lundqvist et al., 2008), speculate that the most significant change will be the shift towards meat- and dairy-based diets, which are more water, energy (and phosphorus) intensive[45] and generate more greenhouse gases per person.

Global food production today is highly dependent on cheap fossil fuel energy. Transporting food all over the world, in addition to mining and manufacturing fertilizers, is only possible while cheap oil exists. However a peak in global oil production is imminent (Royal Dutch Shell, 2008) and alternatives to fossil-fuel-dependent agricultural systems will be required in the future (Pfeiffer, 2006). Food availability is also constrained by water availability. It is estimated that we will need to double the current amount of consumptive water to feed humanity in 2025, based on current practice, however this volume is unavailable and thus innovative strategies to achieve 'more nutrition per drop' will be required (SIWI-IWMI, 2004; Lundqvist et al., 2008).

Similarly, food security is constrained by the availability of, and accessibility to, phosphorus

[45] That is, producing meat and dairy products requires more tonnes of phosphorus, litres of water and megajoules of energy per kilocalorie of food produced.

fertilizers (and the other essential macro-nutrients, nitrogen and potassium[46]). Phosphorus is essential for crop production, yet the main source in modern agriculture, phosphate rock, is non-renewable and current known economic phosphate rock reserves are likely to be depleted in 50–100 years, as detailed in *Paper I*. Innovative strategies for reducing demand for rock phosphate and increasing the recycling of available stocks of phosphorus are also urgently required (described in detail in *Paper I* and in chapter 5). Yet impending phosphorus scarcity has not been mentioned in any of the major discourses related to food availability.

Food *accessibility* is another core theme of food security, although its importance alongside food availability was only really established approximately two decades ago (Ericksen, 2006). There is currently enough food produced in the world, yet over a billion people go hungry because they are either too poor to buy food or lack access to land and resources to enable them to grow food (Fresco, 2009). This suggests we also need to focus on improving access to land and productive resources, increasing investment in human capital (such as public health and education) and improving access to markets for the poor (IATP, 2006). Of relevance here is the sustainable livelihoods approach, which has increasingly gained traction in the development sector over the last decade or so (Chambers and Conway, 1992; Carloni and Crowley, 2005; Carney, 2005; Cotula et al., 2008). According to Chambers and Conway, a sustainable livelihood:

> *comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base*" (Chambers and Conway, 1992, p.6).

According to this approach, access to five key capital assets are required for household livelihood security including: financial capital (such as income and credit), human capital (such as skills and health), natural capital (such as water and nutrients), physical capital (such as equipment) and social capital (such as social support) (Cotula et al., 2008).

Many of the world's hungry are in fact smallholder farmers and their families. An important dimension of food accessibility and household[47] livelihoods is therefore *fertilizer* accessibility and *farmer* livelihoods. Farmer accessibility to fertilizers or fertilizer markets is critical to both livelihood security and global crop yields. Indeed, the president of the International Fund for Agricultural Development (IFAD), Kanayo F. Nwanze, indicates that:

> *Many of the world's poor and hungry are smallholder farmers in developing countries. Yet they have the potential not only to meet their own needs but to boost food security and catalyse broader economic growth. To unleash this potential and reduce the number of hungry people in the world, governments, supported by the international community, need to protect core investments in agriculture so that smallholder farmers have access not only to seeds and fertilisers but to tailored technologies, infrastructure, rural finance, and markets… For most developing countries there is little doubt that investing in smallholder agriculture is the most sustainable safety net, particularly during a time of global economic crisis* (FAO, 2009).

Food '*utilisation*'[48] is another important discourse. To ensure nutritional uptake from consumed food, a balanced diet and healthy bodies free of disease are required. Access to safe drinking water and sanitation, education and awareness can help achieve this (Drangert, 1998; Stockholm Environment Institute, 2005). Food safety is also important in the preparation,

[46] The 'secondary' macronutrients, calcium, magnesium and sulphur are also considered important. Plants also require the micronutrients manganese, boron, copper, iron, chlorine, cobalt, molybdenum and zinc.

[47] A household is defined as a "*group of people who eat from a common pot, and share a common stake in perpetuating and improving their socio-economic status from one generation to the next*" (Carloni & Crowley, 2005, p.2).

[48] The term 'utilization' is used by the GECAFS conceptual framework.

transport, storage and consumption of food. The WHO and the FAO together initiated international food standards in 1961 known as *Codex Alimentarius*, such as *General principles for the addition of essential nutrients to foods* (Codex Alimentarius Commission, 1987).

The Global Environmental Change and Food Systems (GECAFS) program's conceptualization of the food system attempts to integrate all key discourses on food security within a wider framework of global environmental change (for a complete explanation, see Ericksen, 2008). This acknowledges the new global challenges facing humanity as outlined in section 4.1. The GECAFS framework defines food systems as comprising a set of activities, which lead to outcomes that are affected by both environmental and socioeconomic feedback (figure 4-8):

> *Food systems encompass (i) activities related to the production, processing, distribution, preparation and consumption of food; and (ii) the outcomes of these activities contributing to food security (food availability, with elements related to production, distribution and exchange; food access, with elements related to affordability, allocation and preference; and food use, with elements related to nutritional value, social value and food safety). The outcomes also contribute to environmental and other securities (e.g. income). Interactions between and within biogeophysical and human environments influence both the activities and the outcomes* (GECAFS, online)

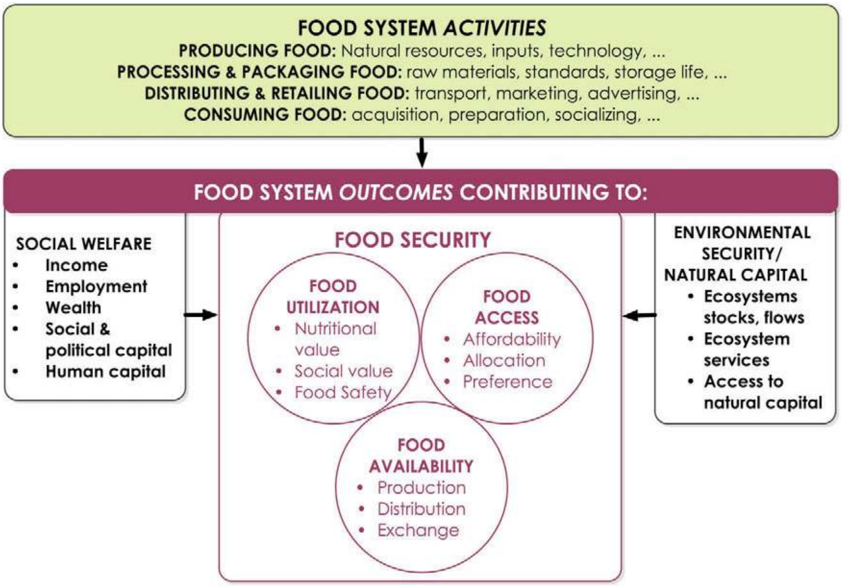

***Figure 4-8**: Conceptualization of the food system, indicating the relationship between food system activities, outcomes (access, availability, utilization) and social-environmental drivers for change*[49]*. Source: Redrawn from Ericksen (2006).*

Despite increasing global demand for non-renewable phosphate rock both in the short and longer term, and its critical role in food production, global phosphate scarcity has not been discussed in any of the dominant debates on global food security and global environmental change. For example, phosphorus scarcity has not received explicit mention within the official

[49] This food systems conceptual framework is embedded within a larger framework indicating its interaction with global environmental change drivers and socioeconomic drivers (see Ericksen, 2006).

reports of the UN Food and Agricultural Organisation (FAO, 2005a, 2006, 2007), the International Food Policy Research Institute (IFPRI, 2002b, 2005), the Global Environmental Change and Food Systems program (GECAFS, 2006), the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD, 2008) and the recent High-level Conference on World Food Security hosted by the FAO (FAO, 2008c). As with the key global environmental change literature described in section 4.1 above, the impacts of global nitrogen and carbon biogeochemical cycles are addressed, as is excessive use of inorganic fertilizers leading to pollution. The *importance* of fertilizers (including phosphorus fertilizers) is often discussed (and indeed was key to the Green Revolution), however this does not include an examination of *where* those sources come from and how sustainable they are in the long term.

The Millennium Development Goals (MDGs) address some of the most pertinent issues facing humanity, including hunger, poverty, water and shelter (UN, 2005). However one significant limitation of the MDGs' conceptualization is the lack of a systems approach, that is, a lack of attention to interlinkages and hence potential synergies between the Goals. A relevant example here is that low-cost community-scale sanitation systems that also recover nutrients for re-use in local food production in say peri-urban food systems (for example, through urine diversion, or biogas digester sludge or other means) could contribute to three goals simultaneously: sanitation, hunger and communities' 'phosphorus sovereignty' (Cordell, 2007a)[50].

4.3 Conceptualising resource scarcity

The development of societies has always depended directly or indirectly on utilizing available natural resources (such as water, biomass, metals), to provide essential services such as nutrition, hydration, energy, tools, mobility and so on. Indeed, a lack of sufficient key resources relative to population has been argued to have led to the downfall of civilisations (Diamond, 2005). Scarcity has been defined in many ways (Graedel, 2002; Molle and Mollinga, 2003; Baumgärtner et al., 2006; Wolfensberger et al., 2007; Wäger et al., 2009), ranging from geochemical scarcity measured by an element's concentration in the earth's crust (Wäger et al., 2009) through to increasing living standards measured by per capita resource use (Wellmer and Becker-Platen, 2002). For the purpose of this research, resource scarcity is fundamentally linked to human activity. That is, scarcity of essential resources is said typically to occur when supply cannot meet human demand due to any number of factors, within a given boundary of time and space, which means that a community's subjective resource needs cannot be met in the short or long term. Figure 4-9 conceptualizes this interpretation and identifies various factors leading to scarcity on a spectrum from supply-side factors to demand-side factors.

[50] This gap (and indeed potential synergies) between water, sanitation and energy MDGs was highlighted in (Stockholm Environment Institute, 2005) (see section 4.4).

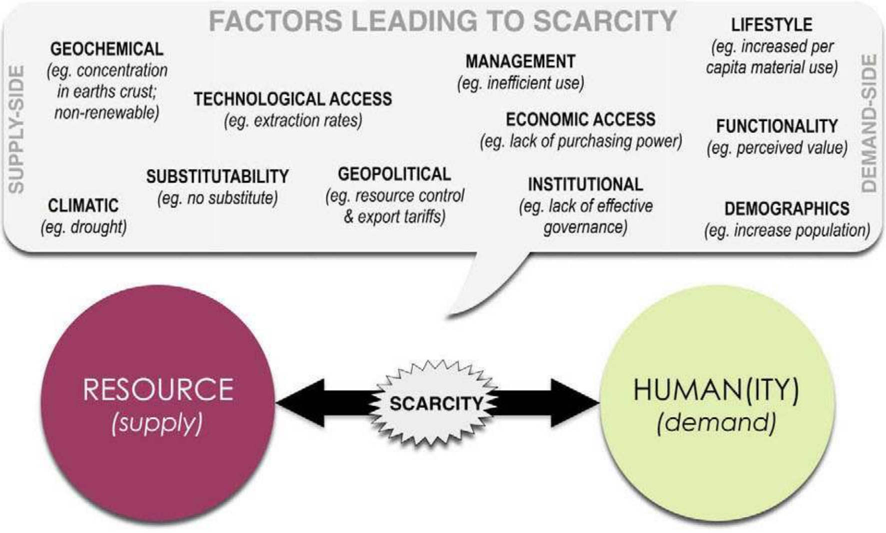

Figure 4-9:*Resource scarcity conceptualized as occurring when societal demand cannot be met by supply due to various supply- or demand-side factors. Source: created for this research.*

Perhaps the most complex demand-side challenge leading to scarcity is population growth. Today's population of 6.1 billion people is expected to peak at around 9.1 billion by 2050 according to the UN's medium population forecasts (UN, 2007). Population growth is limited by the availability of critical global resources (such as food, water, energy) and simultaneously affects the state of the environment (through pollution for example) (Brown et al., 1998) which can in turn limit ecosystem services. The Worldwatch Institute cautions that the UN population projections are based solely on demographic assumptions and do not take into account resource constraints (Brown et al., 1998). Malthus was made (in)famous[51] for his early predictions that growing population would be constrained by the rate of future food supply (Linnér, 2003), however this was thrown into question by technological optimists and is still hotly contested today.

On the supply side, prominent thinkers and scientists have argued that we are living on a finite planet, and hence resource consumption cannot grow indefinitely. In their seminal work *Limits to Growth* in 1972, Meadows et al. proclaimed the overuse of critical global resources would result in collapse of the population (and economy) in the 'standard run' (business as usual) scenario (Meadows et al., 1972). They warned that the practices, processes, production and population of industrial society could not continue to increase indefinitely. Thirty-seven years on, at the first World Resources Forum 2009, Meadows reflected that the basic ideas behind the scenarios have not changed, and that technology will only 'buy time' to make the necessary changes (Meadows, 2009). He further reiterated that society can either 'keep up the goal and change the rules', or 'keep the rules and give up the goals'. Here Meadows means that if

[51] Linnér (2003) clarifies that some of the anti-Malthusian sentiment was not so much about the fundamental notion that food production would not be able to keep up with population growth, but rather about Malthus's assertions about the poor: both that population growth is somewhat a result of the social (e.g. sexual) practices of the poor, and further that improving the livelihoods of the poor may only result in increased global population, which he thought was undesirable.

society is serious about the goal of sustainable development, then this will necessitate a fundamental change in the approach to physical and economic growth.

One of the main theoretical debates related to resource scarcity is whether scarcity is relative or absolute. Underpinning the claim that scarcity is relative, is the neoclassical economics theoretical position that resources can be substituted indefinitely and market dynamics (such as price signals) will ensure that supply will meet demand (Baumgärtner et al., 2006; Ayres, 2007). Countering this, ecological economists such as Nicholas Georgescu-Roegen (Georgescu-Roegen, 1971) and Herman Daly (Daly, 1992) claim that the fundamental geophysical and ecological reality of natural resources has been erroneously removed from the neoclassical economic equation of relative scarcity, and that scarcity can indeed be absolute, due to the physical laws of mass conservation and thermodynamics.

The classical laws of thermodynamics state firstly that energy cannot be created or destroyed (the first Law). The Second Law states that in an isolated system not in thermodynamic equilibrium, heat moves from a hotter body to a cooler body and not the other way around. Total *entropy*[52] will increase in the system as heat energy moves from the hotter body to the cooler body (entropy in an isolated system never decreases). Importantly, this means an external source of energy is required to lower a system's entropy (Baumgärtner, 2003). Many extensions to the classical laws have been made by scholars, including the mass-energy equivalence (drawing from Einstein's $E=MC^2$). As explained by Abeysuriya (2008, p.141, after Daly and Farley (2003)):

> "*Ecological Economics identifies low entropy matter-energy as the ultimate or most fundamental means for achieving human ends…'Low-entropy matter-energy is the physical coordinate of usefulness; the basic necessity that humans must use up but cannot create, and for which the human economy is totally dependent on nature to supply' (ibid)*".

This implies that while mass may readily disperse (increasing the entropy of the system), input energy is required to recover the mass once dispersed. As stressed by Abeysuriya and Daly and Farley above, this has substantial implications for societal use of low entropy matter (such as high grade phosphate rock or fossil fuels). While economic growth has involved converting low entropy materials such as fossil fuels (or phosphate rock in the case of this thesis) into high entropy materials (such as wastes from consumption), the earth's stockpile of high quality (low entropy) materials is finite[53] (Ayres, 1999, 2007). There is only a finite amount of low entropy phosphate rock on the planet, and once dispersed into the environment, higher entropy phosphate rock and other sources will need to be used (since phosphorus has no substitute) and this means more external energy is required to covert the high entropy phosphate into a useful form.

Numerous scholars have since explored this divide, and they have revisited the basic assumptions of each notion (relative versus absolute scarcity). In their analysis of the philosophical and practical underpinnings of each notion, Baumgärtner et al. (2006) explain that the neoclassical economic notion of relative scarcity implicitly refers to 'imaginary needs'

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[52] Entropy is a measure of the amount of energy in a system not available to perform work (The American Heritage Science Dictionary, 2005).

[53] Economic growth also results in the production of low entropy materials and products (for example copper pipes) via metal refining, however lowering the entropy (from processing ore into finished metals products) requires input energy and hence increases the total entropy of the whole system. Further, some metals used in society can be considered dispersed (and hence high entropy), such as the billions of mobile phones in circulation worldwide each contain 0.01% gold (Chancerel and Rotter, 2009).

as distinct from 'elementary needs'. While 'elementary needs' refer to everything necessary for biological survival of humans (such as eating, drinking, sleeping and shelter), 'imaginary needs' refer to subjective human needs and desires beyond mere survival. That is, if elementary needs are not met, one could die, whereas if imaginary needs are not met, one may feel very unsatisfied, but will not necessarily die as a result[54]. Elementary needs are non-substitutable and therefore can be scarce in an absolute sense. Also bridging the divide between proponents of relative versus absolute scarcity, Graedel warns that:

> *history can be a reliable guide to resource availability only if conditions remain the same. In a number of areas, however, conditions related to resource availability are worsening, and the past is no longer prologue* (Graedel, 2002, p.111).

Critics of the 'limits to growth' theory claim that technical progress and human ingenuity have, and will continue to, overcome these limits. Turner (2008) suggests however that multiple criticisms falsely discrediting the limits to growth work provided a political barrier to its use in policy. Two decades after the publication of Meadows' work, in their assessment of future global population, Brown et al. (1998) identified 16 constraints on future population beyond Malthus's dire warning of famine. However, as explained by Linnér (2003), the neo-Malthusian resource debates are as much about resource distribution ("nutritional equity" in the case of food) as they are about physical resource scarcity. Linnér thus articulates Malthusian scarcity as a "fourfold complex" of increasing population, increasing consumption, environmental degradation and unequal resource distribution.

Many of these early resource studies were based on the premise that the earth has a maximum carrying capacity to both provide a population with what is now termed 'ecosystem services', and to assimilate waste. While important, estimating carrying capacity is fraught with difficulty due to a) the inherent complexity and non-linearity of ecological systems, b) predicting the advances technological development can make in extending the carrying capacity of a landscape through efficiency, and c) external future drivers of change that are often unforeseen (Cordell, 2001). Some approaches have somewhat arbitrarily assumed, as a starting point, that the carrying capacity is 10–20% greater than what the natural system (such as a biogeochemical cycle) can sustainably assimilate (Brunner and Baccini, 1991)[55].

A well-known concept similar to carrying capacity, *ecological footprints*, devised by Wackernagel and Rees (1996), aims to account for the resource consumption and waste assimilation requirements for a defined population in terms of the productive land required[56]. For example, in an urban case study in Sweden (Neset, 2005), regional food production (compared to imported food) and meat/dairy consumption were the most significant factors affecting the environmental imprint of the average diet. Today it is estimated that we are using the equivalent of 1.3 earths. That is, we have 'overshot' the sustainable limits of the planet (Global Footprint Network, 2008). From a per capita perspective, the members of the Lindau Group further estimate that current global resource use (estimated at around 20 tonnes/person) would need to be reduced to somewhere around 6 tonnes/person by 2050 in order to be within the

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[54] Baumgärtner et al. (2006) do acknowledge that some core values, such as human rights, freedom or justice may also be viewed as essential to human life and thus fit the definition of absolute scarcity and are theoretically outside the neoclassical economic discipline.

[55] One proposed improvement on this is to estimate the resource flows through a traditional hunter-gatherer community, however this is also based on the assumption that the practices of that society were sustainable and indeed at or below the carrying capacity of the landscape (Cordell, 2001).

[56] Other frameworks that account for material use and waste associated with a material output include ecological rucksack and MIPS (Material Input Per unit deliverable Service) (Schmidt-Bleek, 2008).

earth's sustainable limits (Ekins et al., 2009).

Scientists argue that while we are in a situation of overshoot, there are substantial delays in feedback loops in terms of planetary response or price signals, for example. Figure 4-10 indicates for the case for oil, declines in the remaining resource (for example from 100% to 50%) have to date only resulted in incremental increases in costs. However, using the remaining lower grade resource will result in substantial increases in unit cost (Meadows, 2009). Increasing capital/energy is required, which also results in less capital available for other important sectors of society, such as education, health or agriculture.

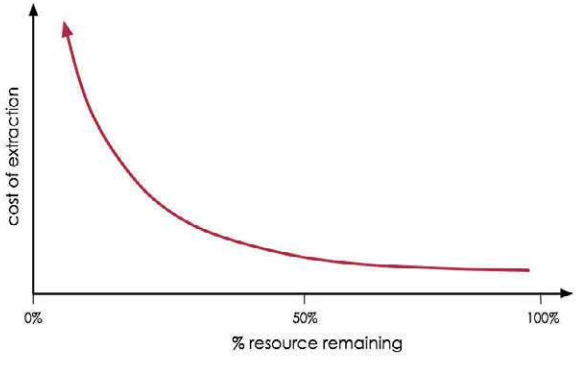

***Figure 4-10**: Cost of extraction (y-axis) of non-renewable resource (e.g. oil) increases exponentially as % resource remaining (x-axis) declines below a certain point. Redrawn after Meadows (2009).*

This is not just the case for oil, but for many other strategic and scarce minerals and metals that are critical to the telecommunications, automotive, electrical or defence industries. For example lithium which is required for rechargeable batteries in electric vehicles (Stamp et al., 2009b) and platinum which is used for catalytic converters and fuel cells (Cohen, 2009). The geopolitical dimensions are also important. For example, China is the world's largest exporter of Rare Earth Elements (REE), holds a 97% market share of processed REEs (National Research Council of the National Academies, 2007) and has in recent years imposed export tariffs on REEs and other major export mineral commodities (USGS, 2007) (including phosphate rock as discussed in chapter 5 and *Paper I*).

There are numerous analytical dimensions of resource scarcity linked to human activity, including the resource unit, the dimensions of sustainability, the stakeholders analyzed, the scale at which the issue is addressed, and which parts of the resource life-cycle are addressed. Figure 4-11 conceptualizes the range of dimensions of resource scarcity that can be analyzed along a resource value chain, from extraction and processing, to consumption, to disposal or re-use. In their conceptualization of the *Mineral Resources Landscape*, Cooper and Giurco (2009) suggest that many sustainability assessments of minerals focus on the material source and technology, and much less on the consumption patterns and 'services' the minerals offer to society.

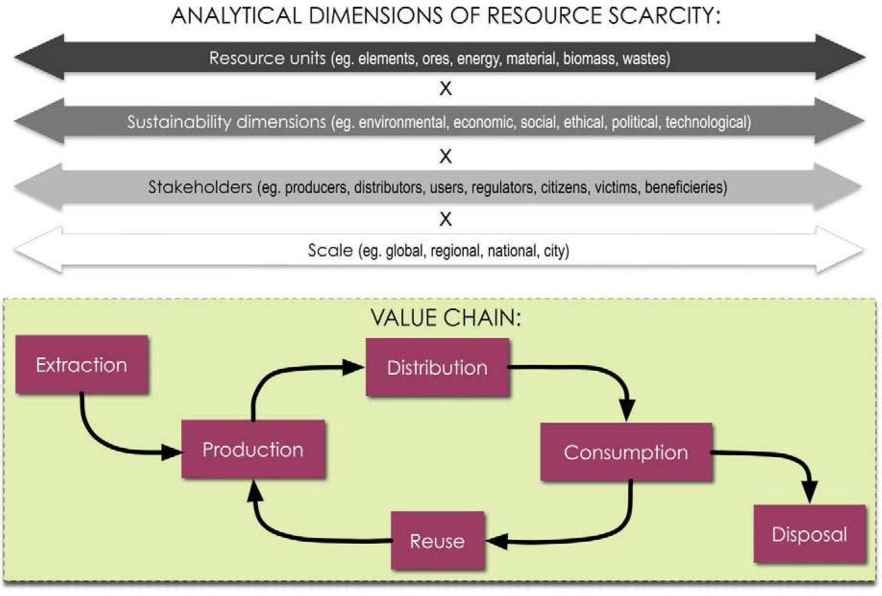

***Figure 4-11**: Some analytical dimensions of resource scarcity along the (simplified) resource value chain. Resource scarcity can be analyzed for a range of resource units, sustainability dimensions, stakeholders and scales. Source: created for this research.*

New international frameworks for addressing global resources scarcity are (re)emerging, such as the World Resources Forum which has launched a Declaration on "*Resource Governance – Managing Growing Demands for Material on a Finite Planet*" (World Resources Forum, 2009), the UNEP Resource Panel (described below), and the EU Resource Strategy, which in part aims to reduce the European Union's consumption of primary raw materials (Makela, 2009). They all call for: a) decoupling of resource use from economic growth and from environmental degradation; b) increased resource productivity and c) extending the system of concern beyond carbon to other important resources.

While scarcity of water and carbon-derived energy have been brought to the attention of the world's decision makers over the past 40 or so years, phosphorus scarcity has received little mention in the resource scarcity discourse[57]. The way resource scarcity is conceptualized has important implications for responses to such scarcity. Young (2005) 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*" (2005, p. 17). Several recent framings demonstrate how phosphorus has slipped through the cracks of integrated frameworks on sustainable resource use. For example, the UNEP's International Panel on the Sustainable Use of Natural Resources classifies important resources as either *food*-related *renewable* resources, or, *non-renewable* resources. However phosphorus belongs fundamentally to both (phosphate rock is a non-renewable resource, while phosphorus is food-related) (figure 4-12).

[57] However, as noted in section 3.5.1, some Industrial Ecology researchers have acknowledged phosphate rock as finite.

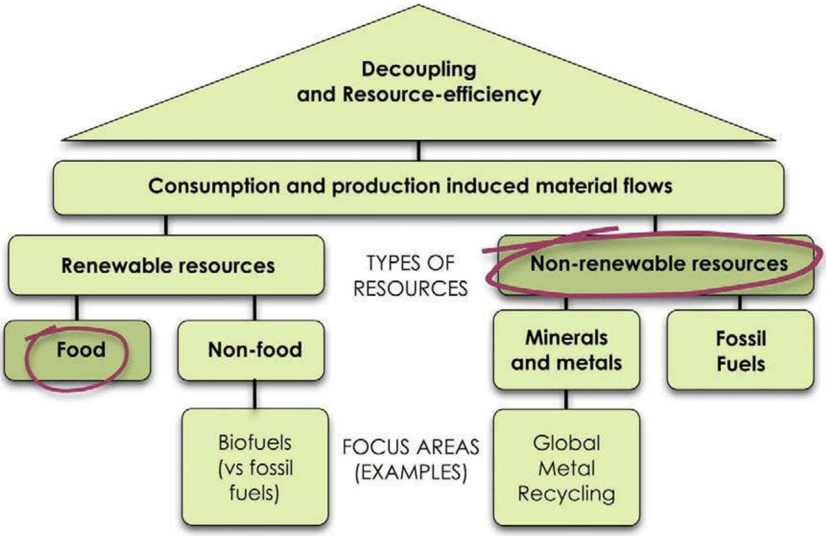

Figure 4-12: *Classification of important resources by the UNEP-facilitated International Panel on the Sustainable Use of Natural Resources, indicating how phosphorus would fall through this net as it is both critical to food production and a non-renewable resource. Source: Redrawn from UNEP (2007b); circles own addition.*

In another example, the UNEP and International Fertilizer Industry Association (IFA) report entitled '*Environmental Aspects of Phosphate and Potash Mining*' (UNEP, 2001) depicts the mineral fertilizer life cycle as an essentially 'closed-loop', rather than its current essentially linear flow (figure 4-13). Whilst phosphorus is indeed returned to the environment after consumption or from losses, the time gap between the environment sink and the source is approximately 10 million years, the processing involves an increase in entropy, and in the intervening time, it causes substantial onsite and downstream pollution and resource scarcity.

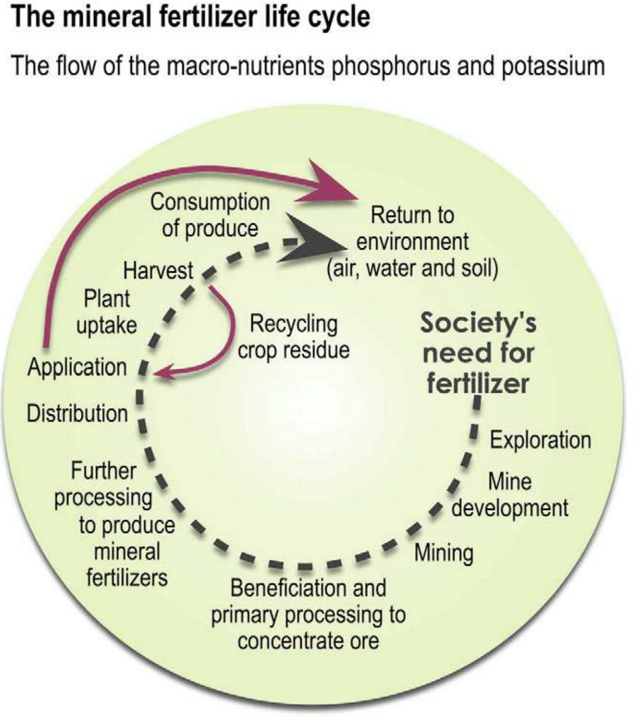

Figure 4-13: *Conceptualization of the 'mineral fertilizer life cycle', depicting how phosphorus and potassium are returned to the environment, essentially implying a closed loop system. Whilst phosphorus is indeed returned to the environment after consumption or from losses, the time gap between the environment sink and the source is approximately 10 million years. Hence this is more an open-looped, linear system. Source: Redrawn from UNEP (2001, fig1.2) citing Sustainable Development and Minerals and Metal.*

4.3.1 Peak everything

As first highlighted by Hubbert in 1949 (Hubbert, 1949), production of oil resources will eventually reach a maximum rate or 'peak' based on the finite nature of non-renewable resources, after which production will decline. Hubbert's peak theory has been verified empirically by analysing the production and reserve data of the lower 48 States in the US, which peaked in 1970 (Aleklett, 2006). While the Hubbert peak has been hotly contested since its conception almost 60 years ago, it is increasingly gaining traction, particularly following the release of the Hirsch Report (Hirsch et al., 2005) and later as the price of oil rapidly increased well beyond US$100/barrel (BBC News, 2008). In November 2007 the then International Energy Agency Chief Economist stated in a noteworthy interview: "*if we don't do anything very quickly, and in a bold manner, our energy system's wheels may fall off – within the next seven years*" (Financial Times, 2007).

In the last few years, there has been a rapid increase in the popularity of peak phenomena, with commentators applying Hubbert's analytical framework to other non-renewable resources, such as other fossil fuels (Heinberg, 2007), other metals and minerals (Heinberg, 2007; Mudd, 2007; Giurco et al., 2009), and phosphorus (Dery and Anderson, 2007; Cordell et al., 2009a). Peak theory has also been applied more conceptually to renewable resources such as water (Gleick, 2008), soils (Friedemann; Chambers, 2008), food (Judge, 2008) and even to human resources such as population.[58]

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[59]. This is because high quality and accessible resources (both renewable or non-renewable) are not infinitely available and homogenous[60]. Production of a *new* non-renewable resource is typically 'easy' (low entropy and hence low energy cost) and profitable at first. However, as the resource is consumed over time, and the 'easy' low entropy resources have been depleted, the lower grade and more difficult to access deposits are exploited. This means more energy, resources and processing costs are increasingly required to obtain the same unit value from the resource. Meadows (2009) notes that the energy/profit ratio of oil today is in the order of 10–30%, while for tar sands the ratio is approximately 2–3%, compared to the 100% net energy yields of oil in the US in the 1930s. Figure 4-14 classifies four theoretical phases of a peak curve in the situation where demand increases[61].

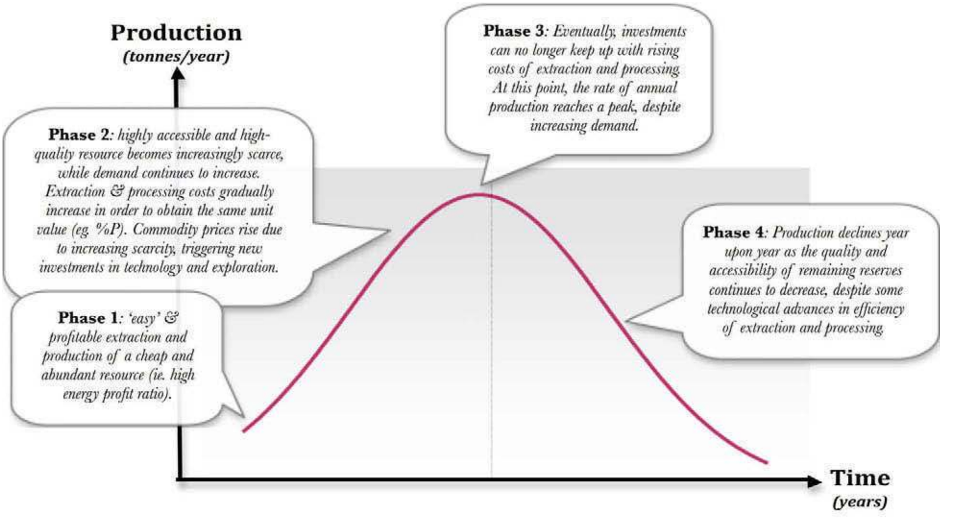

Figure 4-14: *Key theoretical phases of a peak curve during the lifetime of a critical non-renewable resource, where demand continues to increase. Source: created for this research.*

[58] However the concept of peak population is not new, as discussed earlier with regard to Malthus and others.

[59] Indeed, there is a risk that advances in technology with respect to exploration, extraction and refining, will only speed up the rate of depletion, marginally postponing the peak or result in a plateau which would in turn steepen the post-peak decline of production and hence give society less time to adapt (see Kerschner & Cordell, 2007).

[60] We consume them at rates which are orders of magnitudes greater than their natural renewal (see figure 4-15).

[61] If demand decreases due to external factors, production will decrease accordingly, irrespective of supply constraints.

The peak phosphorus analysis undertaken in this doctoral research indicates a peak is likely to occur before 2035, based on industry data (presented in *Paper I*). Peak theory sceptics commonly 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 (Stewart et al., 2005; Smil, 2006). As discussed earlier, 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 sceptics don't deny that resource peaks will one day occur; rather, they dispute the *timeline* and insist a peak is more in the distant future (Caveny, 2006). For example, in the case of phosphorus, as noted in *Paper III,* when key international stakeholders were questioned about the concept of peak phosphorus, the international fertilizer industry expert and the UN fertilizer demand expert both argued that the *demand* for phosphorus may peak before supply is constrained, and reiterated this during recent media interviews:

> *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* (see *Paper III*).

However there is little analysis on which to base this, as discussed in section 3.4.2 on data scarcity.

4.3.2 Comparing non-renewable and renewable resource attributes

Both non-renewable resources (like oil) and renewable resources (like water) can be described as scarce. To further understand why phosphorus scarcity might not be considered a priority next to water and energy scarcity in the debate on global food security or global environmental change, a comparison of the attributes of oil and phosphorus (table 4-1), and water and phosphorus (table 4-2) was undertaken, followed by a general comparison of attributes of renewable and non-renewable resources.

Phosphorus scarcity has many fundamental similarities with oil scarcity (for example both are non-renewable resources on which society currently depends[62]), yet there are just as many key differences. Perhaps the most notable difference is that unlike oil, which is lost once used, phosphorus can potentially be recovered and re-used again and again. Phosphorus essentially has no atmospheric phase so it is not lost to the atmosphere. The following table 4-1 compares and contrasts the attributes of peak oil and peak phosphorus.

[62] Such resources are classified as *GNORK* resources (Global, Non-Renewable Key resources) (Kerschner and Cordell, 2007).

Table 4-1: *comparison of attributes of peak oil and peak phosphorus. Adapted from Kerschner and Cordell (2007).*

Attribute	Oil	Phosphorus*
Dependency	Modern societies dependent on cheap oil. Products made of hydrocarbons are all around us and are crucial for energy and food production, transport.	Similarly for phosphorus, which is essential for food production yet it is predicted that demand for phosphorus will surpass supply of known phosphate rock reserves in the near future.
Peak discovery	Peak oil discovery occurred in 1960s (Aleklett, 2006)	Peak discovery of phosphate rock currently unknown due to lack of available and accessible data.
Peak production *(= peak resource)*	Expected to occur between now and 2020 (Aleklett, 2006)	Peak phosphorus estimated by 2035.
Depletion	At current consumption in about 40 years (BP, 2007)	At current consumption in 50–100 years.
Substitutability	Substitutable, however the sheer quantity of energy provided by oil is difficult to replace and no real alternative is in sight.	Non-substitutable. P (along with N and C) is a critical element for food production. It cannot be manufactured.
Future demand	Future demand for oil is increasing both in per-capita and absolute terms. This is largely due to its link to economic growth.	Future demand for P is predicted to increase at 2.3% p.a., largely due to increased food demand in the developing world. A meat-based diet also consumes significantly more P than a vegetarian diet. Biofuel demand is now another factor competing with food crops for fertilizer demand.
Geographical distribution	Highly skewed global reserves – creates geopolitical tensions (e.g. dependence on Middle East, since US hit peak oil in 1971. The UK with its North Sea oil peaked in 1999. Australia peaked in 2000 (ABC, 2005).	Highly geographically concentrated (reserves are mainly in Morocco and Moroccan occupied Western Sahara), China, US; US reserves to be depleted in 25 years.
Geopolitics	High geopolitical tensions as a result of scarcity and natural distribution e.g. Middle East and US.	Similarly, phosphate rock is likely to experience increased geopolitical tensions due to geographical distribution. Already tensions exist in Western Sahara, Morocco, US.
Food Production	Oil and petroleum products are essential for fertilizer and food production (Pfeiffer, 2006).	90% of global phosphate rock extraction is for food production.

Attribute	Oil	Phosphorus*
Conversion efficiency	Depends on type of use but in the transport sector, which its most important consumer, it is generally very low: around 30% otto motor (i.e. four-stroke engine), and around 40% the diesel engine.	A balanced diet results in depletion of around 22.5kg/yr of phosphate rock (or 3.2kg/yr of P) per person based on current practices. This is 50 times greater than the 1.2 g/d per person recommended daily intake of P.
Fate	Oil is 'lost' once used. It changes form to CO_2 and derivatives and cannot be captured for re-use.	P is an element that cannot be created or destroyed according to the law of mass conservation. It is potentially recoverable if not dispersed to economically unrecoverable concentrations.
Excess consumption (i.e. downstream impacts)	Oil and its derivatives are foreign substances to the natural environment. Hence once extracted it will evidently cause pollution of some sort at critical concentrations. Burning oil as fuel is among the largest contributors to CO_2 emissions and hence to climate change.	Excess P consumption can result in discharges of critical levels of P, potentially eutrophying water bodies, threatening the environment and public health.
Tangibility	Almost all actors, including citizens, understand the significance of oil (i.e. oil = energy) partly because it is a tangible symbol in our society. For example automobile users directly consume oil and petrol stations are ubiquitous.	Very few actors besides farmers and the fertilizer industry understand the significance of phosphorus, as it is far less tangible than oil or water. Whilst humanity also depends on phosphorus, it is consumed indirectly through food. Prior to 2008, most people have never seen phosphate rock in the media let alone in real life.
Arenas	Peak oil phenomenon is currently limited to discussion among concerned scientists and academics, but not in the public arena or in oil/energy decision-making/negotiations arenas.	Until recently, peak phosphorus was a phenomenon not yet accepted in any arena, including global food security, fertilizers, the public arena generally, and the appropriate decision-making arenas for natural resource use.

* all phosphorus data sourced from and explained in *Paper I*.

The following table 4-2 highlights the similarities between water and phosphorus in the context of global food security. The comparison indicates that many of the reasons we are currently concerned about water in the context of food security apply equally to phosphorus, yet there is substantially less attention being paid to the phosphorus challenge.

***Table 4-2**: comparison of attributes of water and phosphorus in food production.*

Attribute	Water	Phosphorus*
Supply vs demand	Water is essential for food production yet it is predicted demand will surpass supply in the near future (Fraiture, 2007).	Phosphorus is essential for food production yet it is predicted demand will surpass supply of known phosphate reserves in the near future.
Future diets	Global trends indicate we will eat more meat in the future. A meat-based diet consumes significantly more water than a vegetarian diet (Smil, 2007).	A meat-based diet also consumes significantly more P than a vegetarian diet.
Food production	70% of global water demand is for crop production (SIWI-IWMI, 2004).	90% of global P extraction is for food production.
Efficiency	A balanced diet results in depletion of 1300kL/yr per person based on current practice. This is 70 times greater than the 50L/d per person considered to be required to satisfy basic needs (SIWI-IWMI, 2004).	A balanced diet results in depletion of around 22.5kg/yr of phosphate rock (or 3.2kg/yr of P) per person based on current practice. This is 50 times greater than the 1.2 g/d per person recommended daily intake of phosphorus.
Recovery potential	A largely untapped source of water for food production is 'green water' (i.e. that part of rainfall that returns to the atmosphere through evaporation or evapotranspiration and is irretrievable once it re-enters the atmosphere (SIWI et al., 2005).	Similarly, untapped sources of phosphorus are 'exchange pools' (such as human excreta) that are temporarily stored for relatively short periods of time in the biosphere and are irretrievable once entering the hydrosphere.
Excess consumption (i.e. downstream impacts)	Excess water consumption can result in the generation of large volumes of wastewater, seriously threatening the receiving environment and public health.	Excess phosphorus consumption can result in discharges of toxic levels of phosphorus, potentially eutrophying receiving water bodies, threatening the environment and public health.

* all phosphorus data sourced from and explained in *Paper I*.

While phosphorus scarcity has many similarities to both water scarcity and peak oil, phosphorus is a far less tangible resource. Water is highly visible and indeed is utilized directly by every person on a daily basis and refined oil is pumped into cars each week, but there are no direct or visible uses of phosphorus in society. It is hidden in the embodied food we eat, and in the excreta we flush down the toilet (see section 4.1). It is not surprising there is most awareness about phosphate runoff/losses from farms and effluent causing algal blooms given the visual nature of an algal bloom and their direct physical, environmental and economic impacts. Further, when the price of oil goes up, drivers feel it the next day but this is not typically the case with phosphorus[63].

Finally, physical and institutional attributes of renewable versus non-renewable resources are compared (table 4-3).

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[63] Farmers purchase fertilizers annually, and usually absorb the price rather than pass it on to the consumer via food/agricultural commodities, however the 2008 price spike was certainly felt by the world's farmers during the next purchasing period.

Table 4-3*: Comparison of renewable vs non-renewable resources, in terms of their physical and institutional dimensions.*

Dimensions	Renewable	Non-renewable
Physical	Stocks tend to replenish at a rate of days to years or decades, thus making them relatively more available again for use.	Stocks do not replenish on a time scale of humanity, (e.g. 10's of thousands to 10's of millions of years).
Institutional	Renewable resources are often managed under natural resource management. They are often under valued economically, hence they are subject to exploitation. Other used renewable resources are often managed as wastes.	Non-renewable resources are typically managed as 'commodities', not as natural resources. In this way, they do directly bear an economic cost, and are tradable on the international market. Used non-renewable resources are also managed as waste products (such as 'hazardous materials' or 'end-of-life' products).

A key physical difference between renewable and non-renewable resources is the timeline or rate of renewal. For example, air (or more specifically oxygen) is renewed at a rate of 'days' through photosynthesis, where the average time it takes for water to evaporate or evapotranspire to the atmosphere and then fall again in the form of precipitation is in the order of weeks to hundreds of years (figure 4-15). Phosphate rock and oil, on the other hand, take tens of millions of years to renew (oil through geochemical conversion of ancient vegetation; phosphate through tectonic uplift of ancient seabeds).

Further, a renewable resource can be classified as non-renewable within given geographical and temporal boundaries. For example, the Aral Sea, a body of water supporting an aquatic ecosystem, is a renewable water source, however many scientists believe it may have been pushed past a tipping point and hence may be non-recoverable (Glantz, 1999). This statement implicitly refers to a time scale, such as say 100–500 years. During this period it may be considered non-renewable, however in 1000+ years this water body could theoretically renew itself.

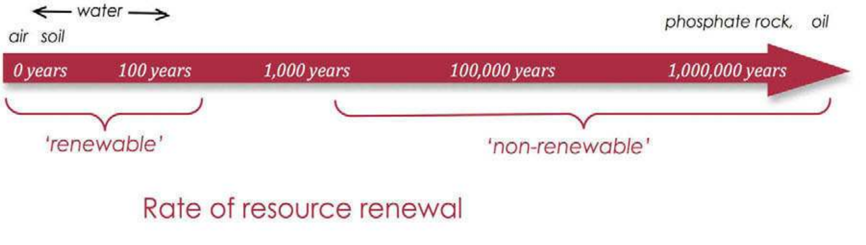

Figure 4-15*: The relative rate of natural recycling of renewable and non-renewable resources on a spectrum of time. Source: created for this research.*

A key institutional difference between renewable and non-renewable resources is that the former are often undervalued in the economic system for their 'ecosystem services', while the latter are usually managed as commodities. This undervaluing or externalising of renewable resources (such as forests or oceans) is well documented and conceptualized as 'The Tragedy of the Commons' (Hardin, 1968), and management consequently as 'Governing the Commons'[64] (Ostrom, 1990). The field of natural resource management, based on environmental and resource economics, aims to value or internalize these resources in economic analyses, where previously they were seen as externalities (Grimble and Wellard, 1997). The paradox to the environmental and resource economist with respect to *non*-renewable resources, is that while they do indeed have an economic value (and hence managed differently to renewable resources), they are often *only* valued as a commodity for a given economic service (like energy or fertilizers in the case of oil and phosphate rock respectively) within a very narrowly defined economic system. This means, their other essential ecological and societal functions are not necessarily valued. Particularly, their finiteness is not taken into consideration, despite their potential scarcity being a direct threat to future generations' ability to produce food and other essential services. This lack of concern regarding essential non-renewable resources is in a sense a 'Tragedy of the *non*-Commons'. That is, rather than mismanagement occurring due to lack of ownership and responsibility for a common good, the mismanagement occurs due to narrowly defined ownership and responsibilities.

This chapter identified and critiqued three interconnected global discourses which phosphorus scarcity fundamentally relates to: global environmental change, global food security, and global resource scarcity. While the International Geosphere-Biosphere Program identifies some of the most important *physical* challenges of global environmental change, and the Earth System Governance Program identifies the *institutional* challenges, neither currently addresses the challenges arising from phosphorus scarcity. Similarly, while phosphorus is clearly critical for the food availability sub-discourse, and has indeed contributed to feeding billions of people over the past century, there has been a significant lack of concern, research and discussion on the security of phosphorus supplies in the future. Finally, a comparison of phosphorus scarcity to oil and water scarcity discourses indicated why phosphorus should be treated as being equally important.

The next chapter shifts the argument from a broad sustainability context to the phosphorus situation itself. That is, fundamental features of phosphorus, how it is perceived and managed, and why this situation is critically unsustainable and threatening future food security. As put forward in the following chapters of this thesis (specifically in chapter 5, 6 and 8), the phosphorus scarcity discourse will need to be integrated in responses to all three of the aforementioned global challenges. However, due to its fundamental role in crop growth, perhaps integration into the global food security discourse will be most urgent.

[64] The term 'Tragedy of the Commons' was famously coined by Garrett Hardin in 1968 referring to the clash between individual interests and the common good (Hardin, 1968).

CHAPTER 5: PHOSPHORUS USE, MANAGEMENT AND PERCEPTIONS IN THE GLOBAL FOOD SYSTEM

Chapter 4 demonstrated the relevance yet current absence of phosphorus scarcity related to food production from the dominant discourses on global environmental change, global food security and global resource scarcity. This chapter then argues in greater detail why phosphorus is so critical to humanity (making effective management vital), yet current management and governance is unsustainable

Phosphorus is essential for all life and hence it is a fundamental component of the ecosystem services that support the earth system and human wellbeing. Humans obtain phosphorus from the food that they consume, but where the phosphorus in food comes from, and how sustainable it is in the long-term is often not the topic of investigation. This chapter therefore critically analyzes how phosphorus has been conceptualized in society, and suggests an emerging new discourse − phosphorus scarcity related to food security − has historically been missing from the major conceptualizations of phosphorus. Further, an analysis of governance structures highlights a current lack of effective governance that would be required to ensure the sustainable management of global phosphorus resources for future food security.

5.1 Conceptualizing phosphorus in society

This section identifies the different co-existing conceptualizations of phosphorus in society relevant to a more sustainable future, with a special reference to the discourses of food production, eutrophication and sanitation.

Phosphorus was chemically identified over 300 years ago. In the late 17th Century the German alchemist Henning Brandt distilled 50 buckets urine through heating and evaporation in search of the legendary 'Philosopher's Stone' which would supposedly turn metal into gold (Emsley, 2000). Whilst he found no such magical stone, Brandt discovered the pure form of phosphorus, which also glowed in the dark. The main use of phosphorus in the 17th and 18th centuries following its chemical isolation by Brandt was for medicinal purposes. However the discovery that bones were a more abundant source of mineral phosphorus in the early 19th century, led to the mass manufacturing of phosphorus matches. White phosphorus was a dangerously flammable element that could now be produced in relatively high quantities[65] (Emsley, 2000). By the 20th century it was a common 'element of war' and Emsley notes that 2000 tonnes of "burning phosphorus" was used in phosphorus bombs on Hamburg during one week alone in World War II. (See Ashley et al. (2009) and Emsley (2000) for detailed accounts of the 'use and abuse' of phosphorus throughout history).

Whilst many Asian cultures (for example) implicitly understood the 'life giving' nature of human excreta for past millennia, its significance to life perhaps became apparent in the Western world when Liebig 'declared' phosphorus the limiting nutrient in plant growth (see section 5.2 below). A century later, phosphorus became one of three (N-P-K) essential nutrient ingredients in commercial fertilizers worldwide. Fertilizer use sextupled between 1950–2000

[65] White phosphorus, an elemental form of phosphorus, is highly reactive and hence not found in nature. White phosphorus is dangerously flammable when exposed to air, can spontaneously combust and is a deadly poison in low doses (Emsley, 2000).

(IFA, 2006a). Domestic cleaning was also transformed in the 1950s through the discovery and subsequent introduction of phosphorus into household detergents (CEEP, 1997). It has only been in the past few decades that the severe consequences of mobilising excess nutrients into the environment (causing eutrophication and dead zones) became apparent (Barnard, 2009). Figure 5-1 depicts the broad evolution of phosphorus discourses since the element's chemical discovery.

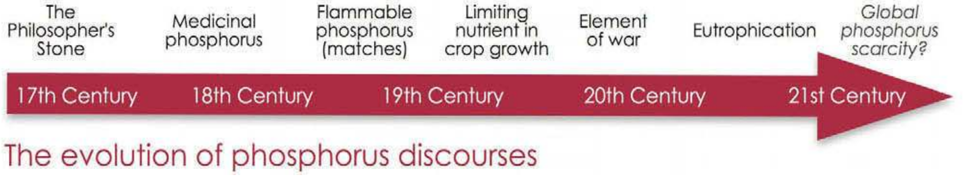

***Figure 5-1**:The evolution of phosphorus discourses: from the Philosopher's Stone to use in war, food production, and more recently implication in water pollution. As argued in this thesis, the newest emerging discourse of the 21st century may be global phosphorus scarcity.[66] Source: created for this research.*

Phosphorus plays many roles in society today – both desired and undesired. At any moment in time, phosphorus fulfils numerous different functions – on vastly different temporal and geographical scales: transporting split-second signals to the brain in the chemical ATP, or immobile as a $Ca_3(PO_4)_2$ molecule in apatite-rich phosphate rock that took tens of millions of years to form, awaiting extraction, or gradually being drawn up from soil solution by plant roots via chemical diffusion, or discharging from our bodies in a momentary drop of urine before being diluted by a flood of flush water to join other household and industry wastewater at a distant treatment plant, polluting water bodies as cyanobacteria, or simply cycling naturally between land, biota and water without being noticed by most of society. Because of its multiple roles and manifestations, phosphorus is perceived quite differently by different sectors. Table 5-1 identifies 12 different forms of phosphorus, each with different perceived societal functions and each relating to different societal sectors.[67]

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[66] These discourses are not exclusive to one another; rather, they can co-exist and change in relative importance to one another as perceived in society.

[67] While not currently representing a major share of the global demand for phosphorus, lithium-iron-phosphate rechargeable batteries ($LiFePO_4$) are used in electric vehicles and currently contain around 60 kg of phosphate per 300kg battery (Haakman, 2008). If this particular lithium-ion battery (which is considered by some as the preferred choice due to its safety and longevity) in electric vehicles largely replaces the internal combustion motor vehicle, this could potentially impact on the future availability of phosphorus for food production, and conversely, phosphorus scarcity could impact on the viability of such electric vehicle batteries.

***Table 5-1**: multiple roles or functions of phosphorus in society. Some functions are inherently biological in nature, while others are due to anthropogenic interventions.*

Form/ manifestation of phosphorus	Key societal function (perceived)	Category of function*	Related disciplines	Related societal sector(s)	Related role(s)
Phosphate rock (apatite)	*1. Source of P for fertilizers* *2. Tradable commodity* *3. National comparative advantage*	Anthropogenic (intentional); geochemical	Geology; business, politics	Mining, investment banking	Geologist, investor, investment banker, distributor, manufacturer
Fertilizer	*1. Increase soil fertility* *2. Tradable commodity*	Anthropogenic (intentional); ecological	Agronomy, business	Agriculture & farming, fertilizer industry, Investment banking	Farmer, agronomist, soil scientist, investor, investment banker, distributor, manufacturer
Crops	*1. Crop growth, ripening* *2. Agricultural commodity* *3. Energy source*	Anthropogenic (intentional); ecological	Crop science; business	Agriculture & farming, food sector, bioenergy sector	Farmer, agronomist, soil scientist, investor, energy provider
Food	*1. Essential macronutrient* *2. Commodity*	Anthropogenic (intentional); biological	Food science, nutrition	Food production; health	Nutritionist, dietician, doctor, householder
Cell membranes, DNA, RNA, ATP	*1. Cell wallstructure* *2. Energy transport* *3. DNA, RNA component*	Biological	Medicine, endocrinology, basic biochemistry	Health	Medical staff, biomedical/ biochemical/ agricultural scientists
Bones	*Bone & teeth formation; metabolism*	Biological	Nutrition; medicine	Health	Medical staff, biomedical staff
Sewage; excreta	*1. Excrete excess not required or assimilated by the body* *2. Recover from sewage to prevent water pollution*	Anthropogenic (intentional); biological	Nutrition; Medicine; civil/ environmental engineering	Public health; Urban planning; Water and sanitation	Sanitation engineer, Water manager
Guano	*1. Source of P fertilizer* *2. Commodity*	Anthropogenic (intentional); biogeochemical	Agronomy, business	Mining, agriculture & farming, fertilizer industry, Investment banking	Geologist, agronomist, soil scientist, investor, investment banker, distributor, manufacturer
Detergent	*Soften water & optimize washing conditions*	Anthropogenic (intentional);	Chemistry	Detergent & phosphate industry	Biochemist
Flame retarder	*Flame retardant*	Anthropogenic (intentional);	Chemistry	Industry	Industrial engineer

Form/ manifestation of phosphorus	Key societal function (perceived)	Category of function*	Related disciplines	Related societal sector(s)	Related role(s)
Matches, white phosphorus	*1. Enhance flammability* *2. Tool of war*	Anthropogenic (intentional);	Chemistry, politics	Defence, match industry	Industrial engineer
Cyanobacteria & algae	*Eutrophication and algal blooms*	Anthropogenic (unintentional); ecological	Aquatic ecology	Water; environmental protection	Water manager, ecologist

** anthropogenic vs natural and intentional vs unintentional*
Sources: Paper I, Paper III and (CEEP, 1997; Emsley, 2000; Johnston, 2000; Millennium Ecosystem Assessment, 2005a; IFA, 2006b; FAO, 2008a; Jasinski, 2008).

The role of phosphorus in food production is arguably the one most significant to society given a) around 90% of phosphorus used globally is for food production and b) there is no substitute for phosphorus in food production and food is a fundamental basis for human societies. Phosphorus in the context of food security is therefore the focus of this research.

However, contemporary discussions on sustainable phosphorus management have overwhelmingly focused on the role of phosphorus in eutrophying water bodies leading to algal blooms and dead zones (Millennium Ecosystem Assessment, 2005a) as explained in section 5.3. To this extent, the main diffuse and non-diffuse sources of phosphorus (leakage from agriculture and effluent discharges respectively) are increasingly a topic of investigation. The fertilizer and farming industries, the detergent industry, natural resource managers, and the wastewater industry have been engaged in improved management to mitigate both the causes and effects (CEEP, 1997; FIFA, 2003; FAO, 2006; IFA, 2007; Mavinic et al., 2009). Despite the connection to agriculture, these fields of research and practice have had little direct relation to the discourse on global food security or limited global phosphorus reserves[68].

Further, multiple co-existing dichotomies can also complicate or confuse societal perceptions of phosphorus and the appropriate management required. Table 5-2 highlights examples of dichotomies (phosphorus *excess* versus phosphorus *scarcity*) occurring at different scales. These are further explained in the following sections of this chapter.

Table 5-2*: Dichotomies in society's perception of phosphorus – both excess and lack of phosphorus are problematic on multiple scales.*

Scale	Excess	Scarcity
Global	Excess phosphorus use can lead to major water pollution of global significance (eutrophication and dead zones)	Depletion of high grade non-renewable phosphate reserves can limit future food production and therefore global food security.
Water bodies	Excess nutrients (eutrophication) can damage aquatic ecosystems	Lack of nutrients (oligotrophication) can also reduce the population of aquatic organisms
Farm	Excess manure can leak from livestock production facilities and pollute water bodies	Lack of access to fertilizers can limit crop growth and adversely affect farmer livelihoods

[68] See section 5.6 for recent developments.

Soils	Excess phosphorus beyond critical soil levels or imbalanced N-P-K nutrient ratios can both pollute and reduce farmer profits	Phosphorus deficiency in soils can limit crop growth
Human body	Excess phosphorus consumption can act as a deadly poison (in extreme cases)	Phosphorus deficiency can lead to physical illnesses (in extreme cases)*

**(National Health and Medical Research Council, 2006).*

5.2 Phosphorus for global food production

Phosphorus is a critical element for crop and animal growth, and therefore food production. There is no substitute for phosphorus in food production and it cannot be manufactured, hence its significance to humanity. This importance of phosphorus is now well established and has been observed by past literary masters such as Victor Hugo in Les Miserables "*our manure…is gold*" (*see Paper I*), and prominent science writers such as Isaac Asimov who described phosphorus as "life's bottleneck": "*We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation—but for phosphorus there is neither substitute nor replacement*"(Asimov, 1974). Even political leaders such as President Roosevelt stated:

> *The phosphorus content of our land, following generations of cultivation, has greatly diminished. It needs replenishing. I cannot over-emphasize the importance of phosphorus not only to agriculture and soil conservation but also the physical health and economic security of the people of the nation. Many of our soil deposits are deficient in phosphorus, thus causing low yield and poor quality of crops and pastures…* (President Franklin D. Roosevelt 1938).

5.2.1 The importance of phosphorus in crop growth

As described earlier, phosphorus is essential in animals for storing and transporting energy as ATP, the structure of cell walls and as a building block of DNA and RNA. Humans obtain phosphorus from food (naturally from plant and animals and to a lesser extent through food additives). Similarly, livestock obtain phosphorus from feed (either naturally from pastures or crops or as feed additives to supplement natural absorption). Plants in turn obtain phosphorus from soil – their roots absorb phosphorus from soil solution (Johnston, 2000). Mineral sources of soil phosphorus originally come from rock containing phosphorus-rich apatite that has taken around 10–15 million years to form (White, 2000). These sources started their life as remains of aquatic life (such as shells) which were eventually buried on the sea floor, and transferred to the lithosphere via mineralisation and tectonic uplift over millions of years and eventually weathered down via wind and rain erosion (see figure 5-2).

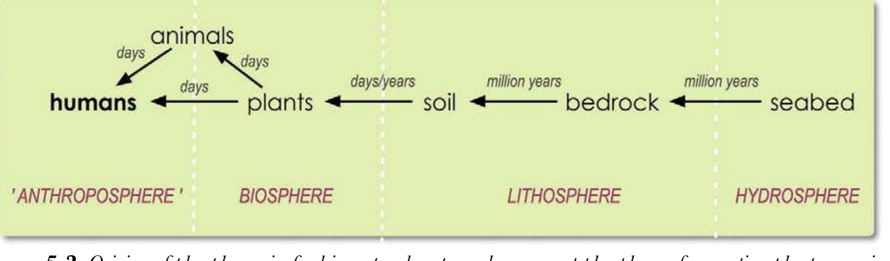

Figure 5-2*: Origins of phosphorus in food in natural systems: humans get phosphorus from eating plants or animals, plants obtain phosphorus from soil solution, phosphorus in soil comes from weathered bedrock, which in turn comes tectonic uplift of the seabed. Time taken for phosphorus to convert from one form to another is indicated in order of magnitude. Source: created for this research.*

Unlike the other essential macronutrients required by living organisms and indeed those comprising the building blocks of DNA (such as carbon, nitrogen or hydrogen) the natural phosphorus cycle has no atmospheric phase[69], meaning flows are restricted to the biosphere, lithosphere and hydrosphere and therefore much less readily circulated naturally. This makes the phosphorus cycle more sensitive to anthropogenic disruptions such as mobilising massive quantities of phosphate from the lithosphere (Gunther, 1997; Smil, 2000b).

Plants require phosphorus for cell growth, the formation of fruits and seeds and ripening (Johnston, 2000). Hence plant phosphorus deficiencies can severely hinder crop yields and fruit/seed development. While phosphorus is highly abundant in nature, it is one of the least biologically available nutrients. That is, the forms in which it exists in the biosphere are often 'unavailable' for plants. Plants can only absorb the soluble inorganic form of phosphorus (known as orthophosphates) dissolved in soil solution. In the natural cycle, bacteria decompose and mineralize dead plant matter in the soil, forming a plant-available form of inorganic phosphorus (figure 5-3).

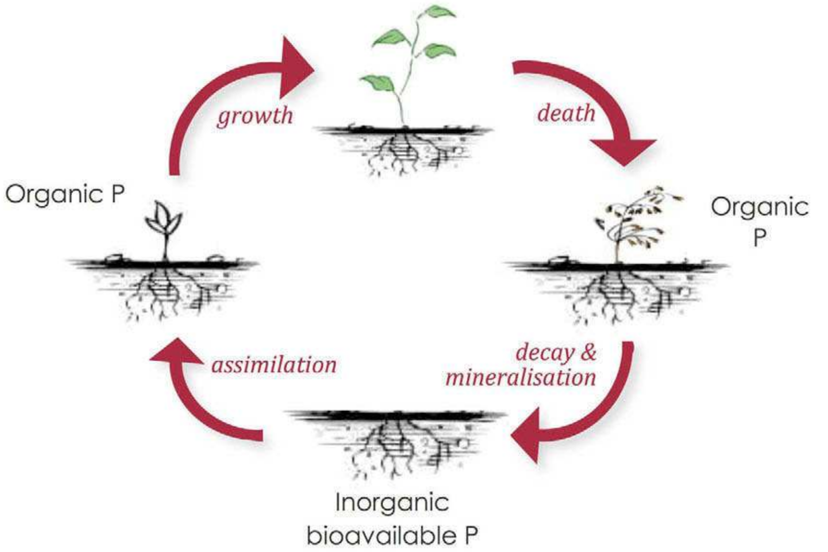

***Figure 5-3**: Biochemical phase of the phosphorus cycle: phosphorus cycles naturally between plant and soil. Organic phosphorus in a dead plant decays, mineralizes to inorganic phosphorus and returns to the soil from where it came, ready to be assimilated via the roots of a new plant. Source: adapted from Cordell (2001).*

Until decades ago it was thought that phosphorus in applied fertilizer could convert to a form in soils permanently unavailable to plants (FAO, 2008a; IFA, 2000b). Today, however, it is understood that the transfer of soil phosphorus from available to unavailable form is reversible (figure 5-4) (FAO, 2008a). This means soils can contain a stock or 'bank' of phosphorus from

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69 A very small amount is circulated through the atmosphere, for example via ash or sea spray, however this tends to be insignificant on a global scale.

which plants can use phosphorus from previously applied fertilizers. This has important implications for efficient use of phosphorus fertilizers.

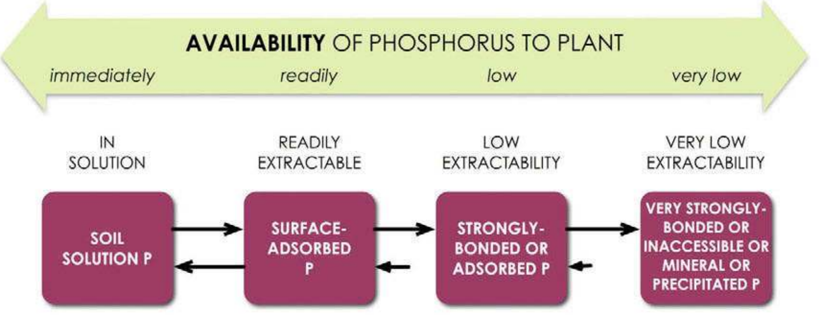

***Figure 5-4**: Availability of soil phosphorus to plants in four different phases, indicating that phosphorus is immediately available to plants for uptake when it is in soil solution, while at the other end of the spectrum, availability is very low when phosphorus is very strongly bonded, inaccessible, mineral or precipitated in the soil. Source: adapted from (FAO, 2008a, p.24).*

Phosphorus reacts readily and adsorbs to other compounds present in the soil, such as aluminium, iron or calcium compounds and organic matter (Johnston, 2000). The strength of the bonds adsorbing phosphorus is dependent on the soil acidity and particle size. This means the amount of phosphorus naturally bioavailable to plants is highly dependent on soil chemistry. Indeed, the recent Millennium Ecosystem Assessment acknowledges this natural variation between the world's soils:

> *P occurs in sufficient supply in young, arid, and neutral soils, although with some exceptions, depending on the nature of the parent material. On the other hand, P often co-limits (with N) plant and animal production on old, highly weathered soils, such as those that dominate tropical Africa, South America, and Australia* (Millennium Ecosystem Assessment, 2005a, p.341).

Comprehensive and up-to-date descriptions of soil-plant behavior, including efficient use of phosphorus fertilizers, are detailed in the FAO's reports (FAO, 2006, 2008a).

Historically, crop production relied on natural levels of soil phosphorus with the addition of organic matter like manure and in parts of Asia, human excreta ('nightsoil') (Mårald, 1998). In 1840 Liebig discovered that phosphorus was the limiting nutrient in plant growth. To keep up with rapid population growth and food demand in the 20th century, concentrated mineral sources of phosphorus were discovered in guano and phosphate rock and applied extensively (Brink, 1977; Smil, 2000b). Figure 5-5 indicates the relative magnitude of the main sources of phosphorus for food production over the last 200 years. The Green Revolution (which included the production and application of mineral fertilizers) in the mid 20th century contributed to increasing per capita nutritional intake and doubling crop yields (IFPRI, 2002b). Though unlike the natural biochemical cycle, which recycles phosphorus back to the soil via dead plant matter (figure 5-3), industrial agriculture harvests crops prior to their decay phase, transporting them all over the world for food production and consumption. This means continual applications of phosphorus-rich fertilizer are required to replace the phosphorus that is removed from the soil when crops are harvested. This is most critical for countries with natural phosphorus deficient soils (such as those regions described above).

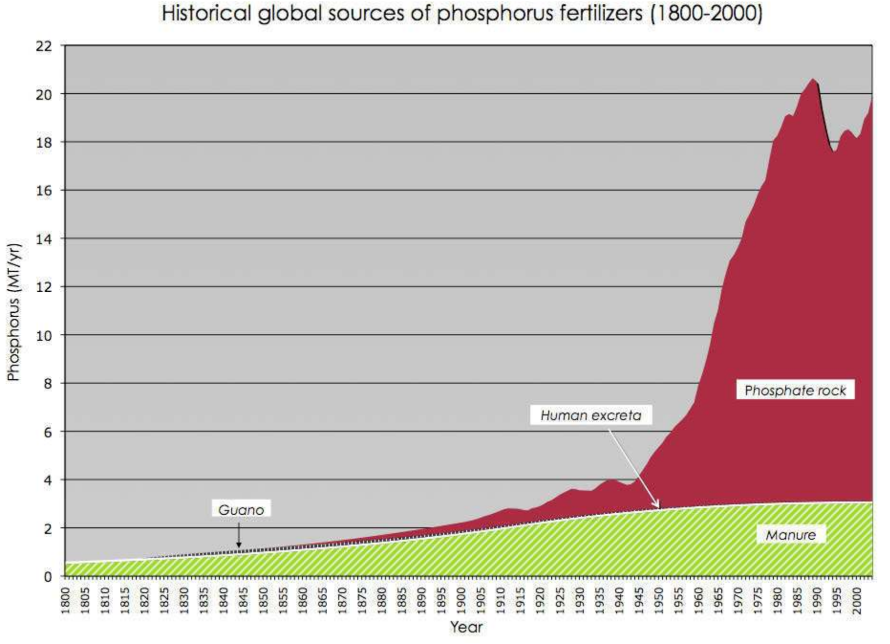

Figure 5-5*: Historical (1800-2000) sources of phosphorus for global fertilizer use, including guano, excreta, manure and phosphate rock. Source: created for this research (Paper I).*

5.2.2 A new challenge: securing phosphorus sources in modern agriculture

There is little doubt today of the importance of phosphorus in producing food at current global yields. Indeed phosphate rock, together with nitrogen and potassium fertilizers, were responsible for feeding billions of people over the past century. The need to raise soil fertility in nutrient deficient areas like Sub-Saharan Africa is relatively well understood by the food security community. However, few discussions have explicitly addressed the emerging challenge of *where* and *how* phosphorus will be obtained in the future to ensure continuous food availability for a growing world population. Today, we are effectively dependent on phosphorus from mined phosphate rock. However, 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. These sustainability implications are analyzed and described in detail in *Paper I*. In summary, the current challenges are:

Environmental and resource challenges:

Phosphate rock, like oil, is a non-renewable resource and approximately 50–100 years remain of current known reserves. Further, a peak in global production – peak phosphorus – is estimated to occur by 2035[70] (figure 5-6). After the peak, supply is expected to decrease year upon year, constrained by economic and energy costs, despite rising demand. While the exact

[70] New unpublished and confidential analyses instigated by US government officials suggests the peak is more likely to occur 2025-2030 based on modest 1.8%p.a increase in demand (Professor Don Mavinic, University of British Columbia, pers comm., 27/9/09). See section 3.4.2 regarding data uncertainty of global phosphate rock reserves.

timing of the peak may be disputed, there is general consensus among industry representatives and scientists that the quality of remaining reserves is declining due to: a) lower concentrations of phosphorus (% P205) in the remaining phosphate rock reserves; and b) increasing concentrations of heavy metals like cadmium and uranium that are toxic to soils and humans and hence must be removed (however, every tonne of phosphate generates five tonnes of radioactive by-product (phosphogypsum) which is currently considered too radioactive to re-use and hence must be stockpiled). Importantly, this means 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. Further, the global trade of phosphate commodities to the farm gate currently relies on fossil fuel energy, yet in a carbon-constrained future, shipping millions of tonnes of phosphate rock and fertilizers around the globe may no longer be appropriate or possible. Finally, these environmental challenges are compounded by ongoing and increasing phosphorus pollution problems leading to eutrophication and dead zones around the world (see section 5.3).

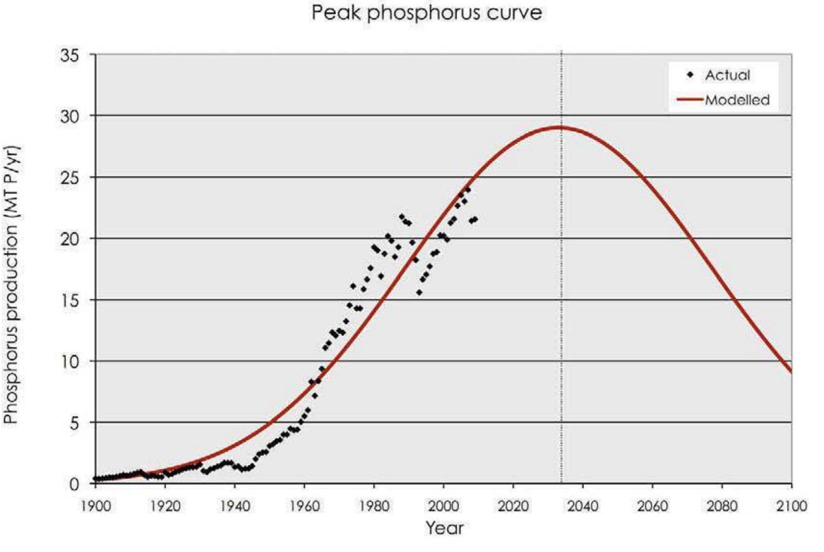

Figure 5-6: *Peak phosphorus curve based on industry data, indicating a peak year of global phosphate rock production in 2033. Source: created for this research (Paper I).*

Economic challenges:

In the long term, it is widely acknowledged that as a result of the above point, and decreasing accessibility of remaining reserves, cheap fertilizers will become a thing of the past. As indicated in figure 4-10, 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 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 were holding back purchasing fertilizers, which partly caused the price to drop.

Geopolitical challenges:

While all farmers need access to phosphorus fertilizers, just five countries control around 90% of the world's remaining reserves, including China, the US and Morocco according to USGS data (Figure 5-7). China has the largest reported reserves, yet in 2008 it imposed a 135% export tariff on phosphate, effectively banning any exports in order to secure domestic supply for food production. The US is fast running out of its domestic high-grade reserves and is increasingly importing rock from Morocco to process into high grade fertilizer for sale on the world market. This is geopolitically sensitive as Morocco currently occupies Western Sahara and controls its vast phosphate rock reserves71. Trading with Moroccan authorities for Western Sahara's phosphate rock is condemned by the UN, and importing phosphate rock via Morocco has been boycotted by several Scandinavian firms.

Social challenges:

All farmers require access to phosphorus fertilizers to ensure a) high crop yields and b) their livelihood security, yet only those with purchasing power can access markets. Further, the 'farm-gate' price of fertilizers can be two to six times higher in Africa than in Europe, due to distribution, storage and transport costs (Runge-Metzger, 1995). 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 deficient72 (IFDC, 2006; Smaling et al., 2006). In the short term the combined fertilizer, food and other resource price spikes pushed fertilizers way beyond the reach of many farmers.

[71] Morocco has occupied Western Sahara since Spain withdrew in 1975. There are serious concerns among the international community, including the UN, due to ongoing human rights violations and the legal rights of Western Sahara to their natural resources as a 'non-self-governing territory' (Corell, 2002). According to the Western Sahara Resource Watch (2007), Morocco's claim is not recognised by any other country and "*numerous UN resolutions support the conclusion that extracting and trading with phosphates from Western Sahara are contrary to international law*". Morocco continues to control the natural resources located within Western Sahara, most notably phosphate rock and fish stocks, due to their economic value. Revenue from the sales of these commodities contributes substantially to Morocco's national income (Hagen, 2008).

[72] Soil nutrient deficiency is due to both naturally low phosphate soils and anthropogenic influences like soil mining and low application rates which have resulted in net negative phosphorus budgets in many parts of Sub-Saharan Africa (Smaling et al, 2006).

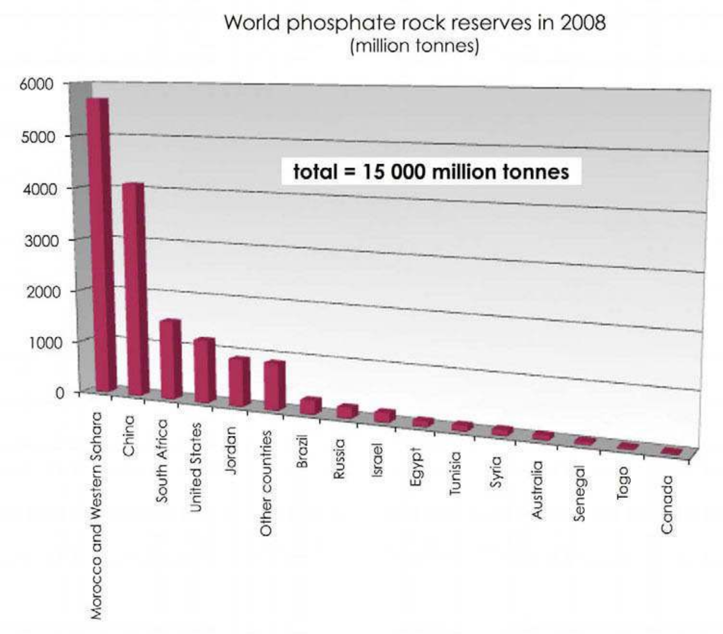

Figure 5-7: *Global phosphorus reserves as reported in 2008. Remaining reserves are highly geographically concentrated and are under the control of only a handful of countries. Note: units are in phosphate rock, not P. Data: Jasinski ((2009).*

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 despite stabilizing fertilizer demand in parts of the Western world where decades of over application means soils are saturated (see figure 5-8). Key factors likely to contribute to the increasing future demand for phosphorus include:

a) increased population growth causing a surge in demand from emerging economies like China and India;

b) per capita increased demand due to changing diets (meat and dairy foods require more fertilizer inputs per unit output);

c) increasing demand for non-food crops like biofuels (energy crops require substantial amounts of phosphorus fertilizers to ensure high crop growth);

d) 'silent' demand from poor farmers with phosphorus-deficient soils. While the UN's Humanitarian Officials have called for a new Green Revolution in Sub-Saharan Africa, including increased access to fertilizers, to mitigate further ramifications of the global food crisis (Blair, 2008), there is little discussion on the finiteness of those phosphate fertilizers in the future.

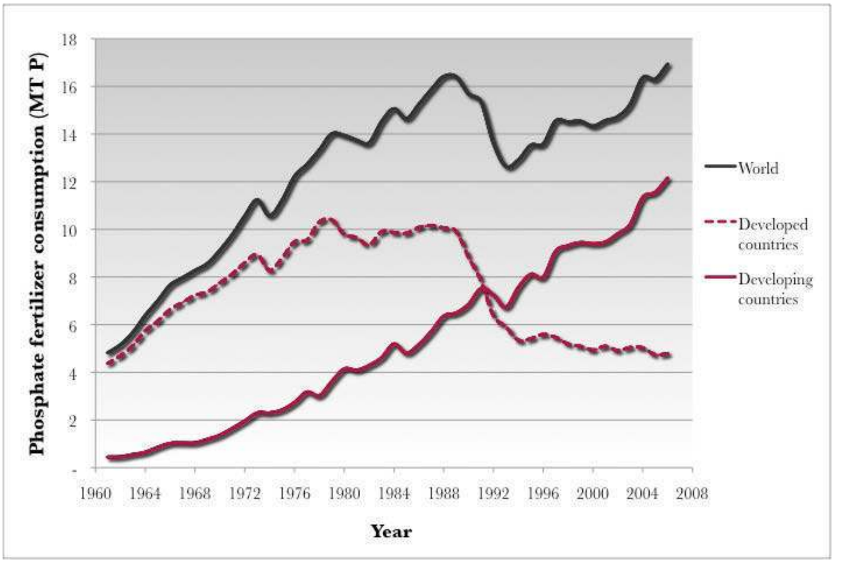

***Figure 5-8**: Global phosphorus fertilizer consumption between 1961-2006 (in million tonnes phosphorus, P). The figure indicates that while demand in the developed world reached a plateau and then declined around 1990, fertilizer demand has been steadily increasing in the developing world. Data: IFADATA* (IFA, 2009a).

These factors mean there is a serious need to investigate the probable future situation (that is, business-as-usual) in addition to how the world's phosphorus needs might be met in a sustainable way. This requires an improved understanding of long-term demand trends (for which there is a serious data gap, as discussed in section 3.4.2), in addition to the potential for other sources of phosphorus. *Paper IV* provides a long-term future analysis of probable, possible and preferred scenarios for meeting future global phosphorus needs for food security. While future annual demand could be as high as 110 million tonnes P/a in 2050 compared to today's 15 million tonnes P/a[73] if the demand pressures above persist unchecked, hypothetically demand could be as low as 4 million tonnes P/a in 2050 if the global population received precisely the phosphorus required for healthy bodily functions (that is, 1 to 1.5g/person/day) and losses were minimized. A more likely scenario was calculated to be somewhere in between, 67 million tonnes P/a by 2050 (based on a 2% p.a increase to 2050) (see *Paper IV* for detailed assumptions). The key here is that this most likely demand could not be met by the supply of high-grade phosphate rock (due to the constraints outlined earlier), hence the potential for alternative supplies (and demand measures) was assessed in *Paper IV*. This scenarios analysis, while indicative due a lack of available and reliable data, suggests a high recovery and re-use rate of all sources of phosphorus may be necessary to meet the future global demand.

[73] This is the estimated amount of elemental phosphorus in phosphate rock used for fertilizer production.

Irrespective of the *source* of phosphorus, the *use* of phosphorus in the entire food system is currently extremely inefficient. The global phosphorus flows analysis through the food production and consumption system in figure 5-9 (and detailed in *Paper I*) found that approximately 80% of the phosphorus in phosphate rock mined specifically for food production never actually reaches the food on our forks – it is lost at all key stages from mine to field to fork.

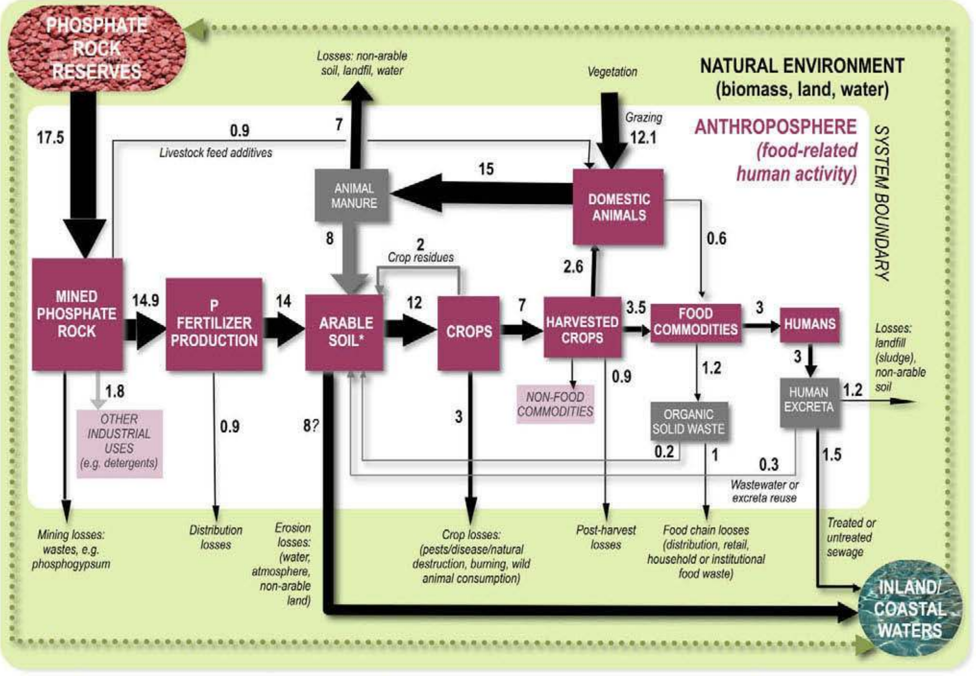

Figure 5-9*: Key phosphorus flows through the global food production and consumption system, indicating phosphorus usage, losses and recovery at each key stage. Units are in million tonnes phosphorus/yr. While phosphorus in the natural system cycles at rates of 'millions of years', flows in the human food system cycle orders of magnitude faster at 'days to years'. Source: created for this research (Paper I).*

While there is a lack of data and substantial uncertainty regarding some figures in the flows analysis[74], such analysis is important because it nevertheless indicates that phosphorus scarcity is a result of mismanagement of phosphorus, in addition to physical constraints. Further, this means:

a) there is substantial potential for reducing the demand of phosphorus through reducing losses (for example by reducing disposal of edible food by supermarkets or households), increasing efficiency and even influencing diets to less phosphorus-intensive foods;

b) the unavoidable losses (for example banana peels, excreta) can be recovered and re-used productively as a source of phosphorus in the future, for example, around 3 million tonnes of elemental phosphorus are generated in human excreta each year,

[74] See Appendix A for data sources and assumptions, and section 3.4.2 for discussion on data uncertainty.

most of which is not productively re-used today; and

c) reducing losses and recovering the unavoidable losses will also have a positive impact on water pollution (particularly from agricultural and excreta sources).

With attention to figure 5-9, losses (and hence opportunities for improved management) from mine to field can occur at the following key stages:

- **mining, beneficiation and transport** – some phosphate is lost during beneficiation (concentration) process whereby contaminants (such as iron phosphate) are removed and discharges to rivers or contained (UNEP, 2001). Phosphate is also lost via spillages during storage and transport of phosphate rock. Some storage and transport losses could be reduced through improved management and technical practices.
- **fertilizer production, handling, storage and transport** – phosphate is most notably lost in phosphogypsum byproduct generated during processing of phosphoric acid (phosphate rock reacted with sulphuric acid). Other losses can occur from spillages (e.g. from torn fertilizer bags), spoilage, theft and other losses during handling, storage and transport (IFA, 2000a, 2000b). While the phosphorus in phosphogypsum stockpiles is of a substantial amount (4-5 tonnes generated for every tonne of phosphate produced), it is currently not used due to radioactivity concerns of phosphogypsum. Some storage and transport losses could be reduced through improved management and technical practices.
- **fertilizer application and crop uptake** – This typically accounts for the largest system losses, as plants only take up a small fraction of the phosphate in applied fertilizers. The remainder is temporarily 'locked-up' in soils in a form unavailable to plants (figure 5-4), or lost from the field via erosion or runoff. The options to increase efficient use of phosphorus by crops and reduce losses in this stage range from improving timing and placement of fertilizers; balanced fertilization (i.e. appropriate N:P:K ratio); consideration of crop varieties that use phosphorus more efficiently; improvement soil quality management to 'unlock' stored phosphorus and transforming to bioavailable form; introduction of microbial inoculants to improve root uptake of nutrients (see *Paper IV* and (FAO, 2006) for greater detail).

While phosphorus is lost from mine to field in the form of phosphate rock or phosphate, it is also 'lost' from field to fork in the form of organic waste (such as the phosphorus contained in food waste or excreta) or conversion losses from feed to animal products. Although up to 50% of phosphorus in harvests is estimated to be lost in food production and consumption, these 'post-harvest' losses have been largely ignored and the focus to date has been on reducing phosphorus losses in agriculture.

Lundqvist et al (2008) introduce a typology for describing field to fork losses in order to analyse water lost in the food system[75]. While this typology can also be extended to phosphorus losses, the terms *avoidable* and *unavoidable* losses have been retained in this thesis for consistency and simplification (for example in *Paper IV*). Avoidable phosphorus losses generally implies increased efficiency measures would be a suitable response, whereas unavoidable phosphorus

[75] *Losses* are differentiated from *wastage* in that the former are generally unavoidable (such as crop residues), whereas the latter is avoidable and typically due to disposal of edible food in the latter part of the food chain. Further, *spoilage* refers to food spoilt during transport, storage, processing and packaging. Finally, *conversion* losses refer to losses when crops are converted to livestock feed to produce animal products (Lundqvist et al, 2008).

losses could be managed through recovery and reuse of the organic material. Current sources of avoidable and unavoidable losses (and hence potential points for increased efficiency or recovery or phosphorus contained in organic material) from field to fork include:

- **crop storage, processing and trade** – once crops are harvested, they need to be processed into food, feed or fibre. Losses can potentially occur during storage (e.g. spoilage due to pests and disease and spillage), processing (e.g. by-product crop residues not required for primary processing), trade (e.g. spillages or losses). Some of these losses may be avoided through improved management or technical practices, however some percentage may persist. Substantial losses also occur when crops are converted to animal products (approximately 40% of the world's harvested crops are used for feed production, returning 10% to the food system as meat) (see *Paper I*). Responses to these conversion losses can range from efficiency measures such as breeding and genetic variations to improve animal uptake of phosphorus, and reducing meat-based diets globally, to recovery options like reusing manure and animal meal as a source of fertilizer and soil conditioner (*Paper II*).
- **bulk food processing, storage, trade** – losses that occur when converting processed agricultural commodities into food commodities, ranging from husks of grains (for processed white rice, bread for example), to losses due to damage, spoilage or below-standard products during trade. Many products today have a extensive associated food miles due to the longer distances and more processing steps involved in the globalised food commodity chain, leading to increased wastage (Ericksen, 2008; Lundqvist et al, 2008). Producing food closer to the point of demand – mostly demand from cities – could reduce food waste in addition to energy, water and other resources. Urban and peri-urban agriculture is one example (FAO, 1999) (discussed further in section 5.2.3).
- **food retailing** – losses that occur during retailing of food items, including spoilt or unspoilt food discarded at supermarkets, markets, other food outlets. Food safety is important in food retailing, however many supermarkets are under consumer pressure or even legal obligation to discard (not sell) food past the stated expiry date, even if the food is perfectly edible (Lundqvist et al, 2008).
- **food storage, preparation and consumption** – losses that occur typically at the final destination prior to or during consumption (such as spoilage in household fridges or pantries, potato peelings during preparation to edible or inedible dinner plate scraps. In some parts of the developed world (such as the UK), 60% of food waste is estimated to be edible, and hence avoidable by improved food and meal planning) (WRAP, 2008).
- **excretion, solid waste management** – this includes both human excreta which may or may not be treated prior to disposal or reuse, and food organic waste which is either informally dumped, centrally disposed, incinerated or processed and reused (or a combination of the above). If this organic matter is not mixed with toxic solid waste (which may contain heavy metals from industry or other pollutants), it can more readily be reused as fertilizer and soil conditioner.

5.2.3 The issue of scale

Finally, while an integrated global scale analysis is of a critical importance, findings from analysis on the global scale are not entirely transferable to a regional or local scale, and vice versa (IDGEC, 2006). The phosphorus situation can vary widely from region to region in terms of natural aspects (such as the soil type) and socio-economic aspects (such as the degree of food security or national dependence on fertilizers) (Runge-Metzger, 1995). The regional analysis presented in figure 2 of *Paper I* indicates that the African continent is simultaneously the world's largest exporter of phosphate rock and the continent with the largest food shortage. Further, in Sub-Saharan Africa, where at least 30% of the population is undernourished, fertilizer application rates are extremely low and 75% of agricultural soils are nutrient deficient (*Paper I*). The more in-depth Australian national case study presented in *Paper V* demonstrates very different regional phosphorus issues at play. For example, Australia is a net food-producing nation that simultaneously has naturally phosphorus-deficient soils and has invested heavily in export industries that rely on intensive phosphorus use (such as the meat industry). Further, the greatest phosphorus losses in the Australian system occur prior to food production (see figure 5-10). *Paper V* explains this in greater detail.

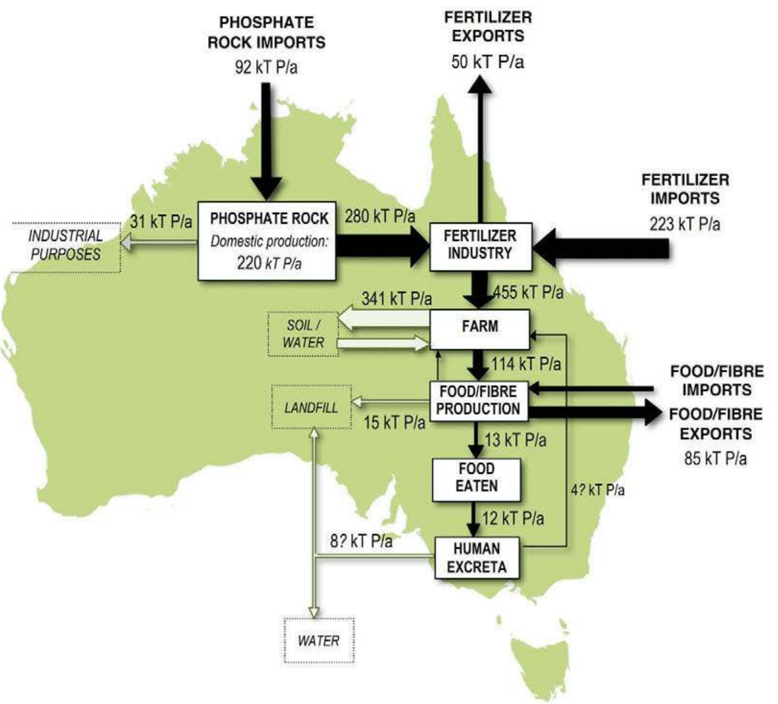

Figure 5-10. *Major phosphorus flows in the food production and consumption system in Australia. The phosphorus content in the production, consumption, excretion and trade of fertilizers and food are indicated in thousand tonnes per year. Source: created for this research (Paper V).*

Regional differences and drivers mean national analyses and context-specific strategies will be required to respond to future phosphorus scarcity. Important phosphorus indicators or characteristics for a regional or national analysis are provided in the recommendations (section 8.2).

In addition to regional and national analyses, also of interest is the spatial distribution of phosphorus due to urbanisation. The concentration of organic phosphorus sources and sinks in the global anthroposphere is highly dependent on the concentrations of populations because at a household level, humans demand phosphorus in food, and excrete phosphorus in urine and faeces. That is, as the world increasingly becomes predominantly urbanized, urban centres will become 'phosphorus hotspots' from human excrement and food waste, as indicated in figure 5-11.

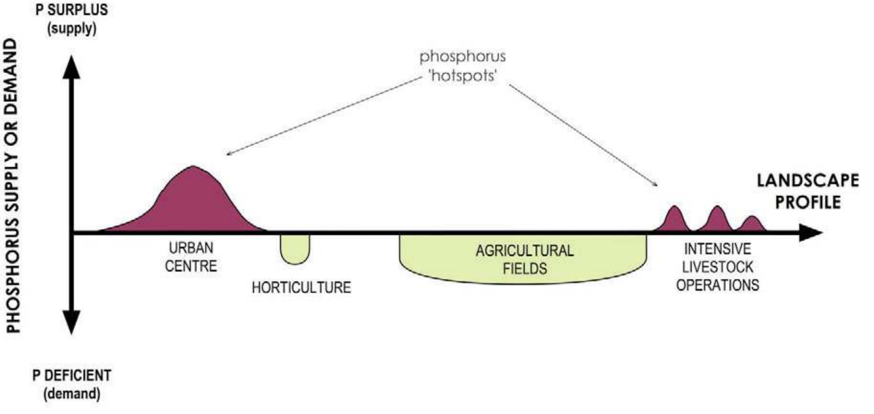

***Figure 5-11**: Spatial profile of an urban-rural landscape – indicating that while agricultural and horticultural fields demand continual phosphorus fertilizers, cities are 'phosphorus hotspots' of food waste and human excreta that could be productively utilized to meet some of the fertilizer demand. The phosphorus in the 'hotspots' originated from local or distant agricultural fields, hence returning the phosphorus to these sources would be closing the loop to an extent. Source: created for this research.*

While nutrient flows from food to human excrement typically found their way back to land in the past, today they more often end up in waterways via wastewater from urban centres (Drangert, 1998). Recycling nutrients in human waste back to agriculture differs between rural and urban areas, and as the global population migrates to urban centres, so does the source of 'humanure' and simultaneously the location where food is needed. This presents a significant opportunity for urban agriculture fertilized by human and animal waste, previously unexplored in detail at the global scale. While urban and peri-urban agriculture fertilized by human excreta and other wastewater fractions is practiced in a planned or an ad-hoc way in some parts of the world such as direct wastewater re-use (Drangert, 1998; World Bank, 2005), its potential to meeting future food security in a sustainable way on a global or even a regional scale has not yet been assessed in a substantial way. Gumbo (2005) provides a thorough analysis for an urban shed in Harare, Zimbabwe, indicating that the fertilizer value of the urine produced by urban dwellers in the case study catchment could sustain the agricultural activities in the surrounding area. The concept of eco-industrial parks in industrial ecology (Ayres and Ayres, 2002) could inform a spatial analysis of how human excreta could be feasibly and logistically collected, converted to fertilizer and re-distributed to urban and peri-urban agriculture in an efficient sustainable manner. However undertaking such a local analysis was outside the scope of this doctoral research.

5.3 Phosphorus as an environmental pollutant

While phosphorus is also essential for life in aquatic environments, excess nutrient loads, or eutrophication of inland and coastal waters has now become an environmental problem of global significance (Steffen et al., 2004; Millennium Ecosystem Assessment, 2005a). Eutrophic waters can lead to algal blooms, which a) block sunlight, reducing the dissolved oxygen and resulting in anoxic bottom waters, and b) following the algae's death and decomposition, toxic compounds are released which result in substantial fish kills and reductions in aquatic biodiversity (Correll, 1998). In addition to critically threatening aquatic ecosystems, toxic algal blooms also result in significant economic and social costs, in the form of losses to fishing and recreational industries and grave threats to drinking water sources (Chudleigh and Simpson, 2000). Dead zones or serious algal blooms are occurring from Chesapeake Bay in the US to the Baltic Sea to Australia's Great Barrier Reef (Chudleigh and Simpson, 2000; Commonwealth of Australia, 2001; HELCOM, 2005; Mörth et al., 2007; World Resources Institute, 2008). In rare instances, a condition opposite to eutrophication known as oligotrophication (lack of nutrients) can occur, which can limit fish and aquatic populations' ability to breed (Anders and Ashley, 2007). Anders and Ashley demonstrate that in some instances, lake fertilization is required to re-establish fish populations, as is the case for salmon in British Columbia in Canada.

While nitrogen is often the main nutrient causing marine-based algal blooms, phosphorus tends to be implicated in blooms in inland water and estuaries (Millennium Ecosystem Assessment, 2005a). Soil erosion due to agriculture (and other land use changes) is the largest driver of phosphorus mobilized to water bodies. Unlike nitrogen, phosphorus is not soluble and does not leach to groundwater in significant quantities. Both natural and fertilizer-derived phosphorus is transported from land to oceans or lakes by water or wind primarily adsorbed to soil particles. The other major source of phosphorus is municipal wastewater. A fundamental (and relatively well understood) difference between the nature of these two sources is that phosphorus pollution from agricultural sources is slow, diffuse or 'non-point', whereas wastewater is typically a point source and results in a more rapid phosphorus flux (such as a pipe outlet) (Brunner and Baccini, 1991). This has implications for the prevention or management of eutrophication.

While eutrophication problems are complex and far from 'solved', there is global awareness of the problem, numerous regional analyses and concerted action being taken to mitigate the problem (Chudleigh and Simpson, 2000; HELCOM, 2005; Millennium Ecosystem Assessment, 2005a; Tonderski et al., 2005; Mörth et al., 2007; World Resources Institute, 2008). However, phosphorus scarcity has rarely been acknowledged in the same discussions.

5.4 Phosphorus recovery and re-use in the sanitation sector

As a consequence of the eutrophication problems described above, some countries today require wastewater treatment systems to remove phosphorus from effluent prior to discharging into water bodies to prevent such pollution. Hence phosphorus has become an important indicator of wastewater treatment (European Commission, 2000; SEPA, 2002; Tangsubkul et al., 2005; Barnard, 2009). The phosphorus in wastewater comes from industrial and household sources such as detergents, but overwhelmingly the largest source today is human excreta[76].

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[76] However Barnard (2009) notes that until the 1970s when environmentalists pressured governments to ban phosphorus in detergents in some regions, detergents often represented half the phosphorus in wastewater.

Figure 5-12 indicates typical sources of phosphorus and other nutrients in household wastewater (Johansson, 2001).

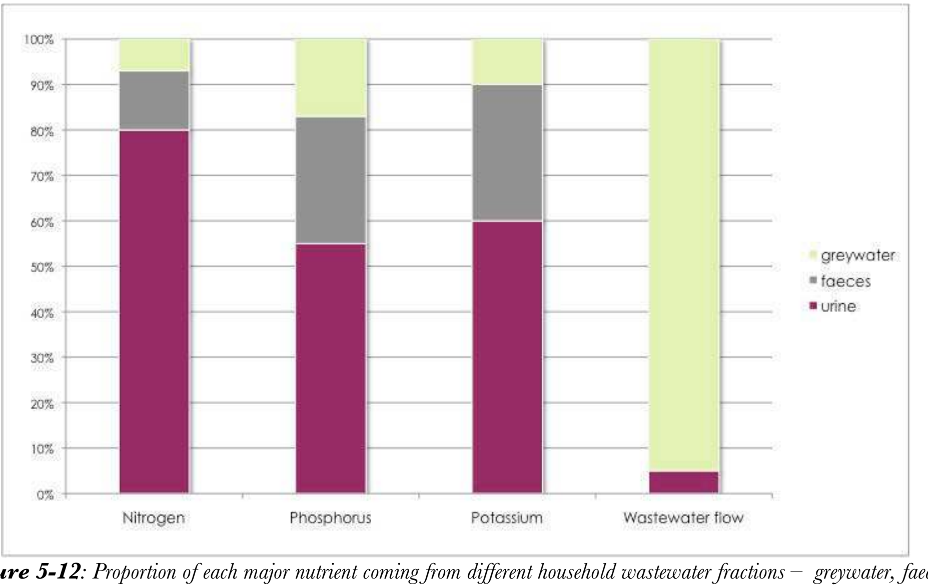

***Figure 5-12**: Proportion of each major nutrient coming from different household wastewater fractions – greywater, faeces and urine. Source: redrawn from Johansson et al (2001).*

Historically, sanitation systems around the world were ad hoc, onsite and certainly did not involve flush water, pipe networks or treatment plants. In the West, it was only in the 1850s during a severe cholera epidemic in London that John Snow isolated the disease vector to a water pump located near raw sewage (Hamlin, 1990). What followed was a large-scale implementation of sewerage systems across cities of the Western world. Water was used as a transport medium to flush pathogenic excreta as far as possible from densely populated cities (Drangert, 1998; Abeysuriya, 2008). These large-scale centralized sewerage systems were mirrored in urban centres around the world. Indeed, the 'sanitation revolution' was hailed by the *British Medical Journal* as the biggest medical advancement since 1840 (Ferriman, 2007). This public health feat involving flush water was eventually followed by more formal institutional arrangements – at all decision-making levels from local management through to international policy (Abeysuriya, 2008).

Today sanitation is almost unquestioningly embedded within the theme of water – both physically and conceptually, giving rise to the commonly used term in the field, 'WatSan' (water and sanitation). This embeddedness is institutionalized in norms and conventions as exemplified by the very term 'wastewater', or the eminent World Water Week that implicitly includes sanitation (often perceived by some as water's 'second-class' cousin). It can be argued that use of the terms 'waste' and 'water' are in fact inappropriate and redundant in sustainable sanitation futures. Since the inception of the flush toilet around 1820, *waterborne* sanitation systems have been viewed as an essential part of human settlements (at least in the Western world), though it is increasingly being acknowledged that this is not the only mechanism for sanitising human excreta. And in an age of regional and global water scarcity, there has never been a more pressing time to reconsider sanitation's link with water (Mitchell and White, 2003;

Cordell, 2006).

Perhaps even more pertinent than decoupling sanitation from water due to increasing water scarcity, is removing the notion of 'waste' from *wastewater* due to the pressing need to re-use excreta as a fertilizer source for food production (for the reasons presented in this thesis). The link between sanitation and food has been largely overlooked by modern societies and is evident in our current institutional arrangements (Cordell, 2006). Yet human excreta contains all the major nutrients needed by plants N-P-K essential for crops growth in the correct ratio. The Chinese have been reusing excreta as fertilizer for 5000 years, and Japan for 1000 years (Matsui, 1997). Today we flush almost all these nutrients in our excreta out to sea – including some 3 million tonnes of elemental phosphorus each year (see *Paper I*). In the long-term perspective, Drangert (2009) conceptualizes this as a temporary stage in history where the sanitation-food link has been disconnected. Gumbo (2005) depicts the sanitation evolution throughout human history from its association with food production in the early civilisations and Middle Ages, through to possible ecological sanitation in the future (figure 5-13).

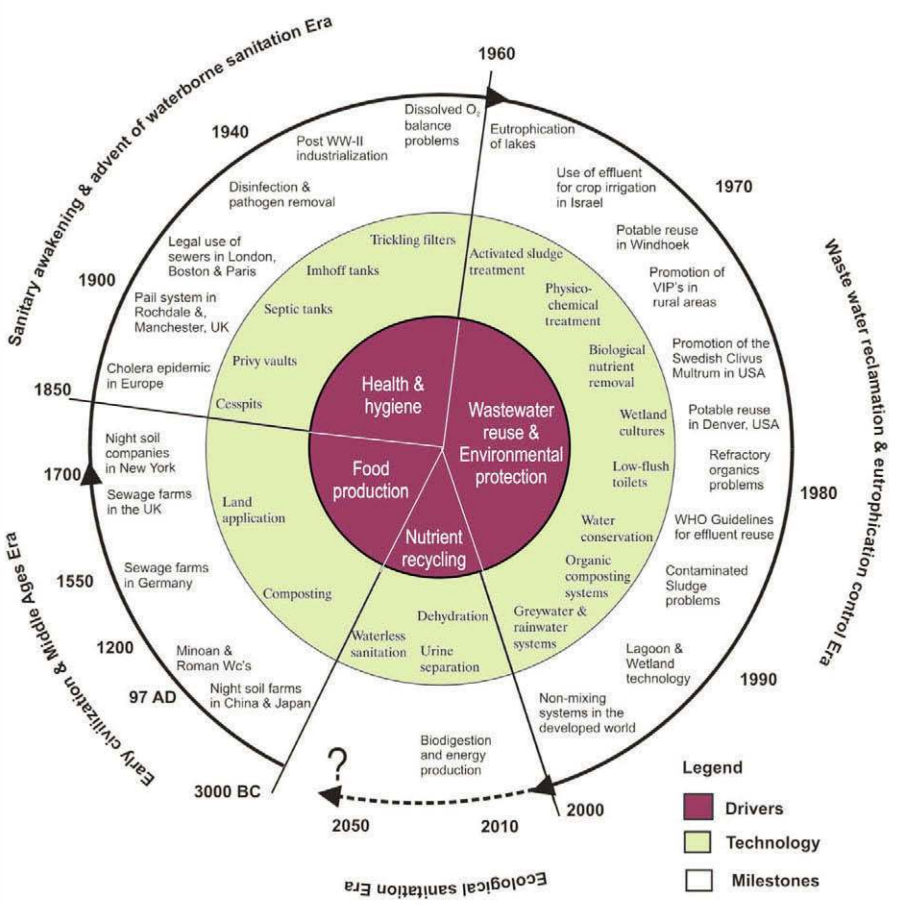

Figure 5-13: *Evolution of sanitation throughout human history, from 'Early civilisation and the middle ages Era', to the 'sanitary awakening and advent of waterborne sanitation era', through to the 'waste water reclamation and eutrophication control Era', and possible future 'Ecological sanitation Era'. Source: Redrawn from figure 10 in Gumbo (2005).*

There are several sanitation discourses and technologies today that do support the recovery and re-use of nutrients, from small-scale greywater systems for example, source-separating composting toilets, wetlands for recovering nutrients, to more large-scale high-tech recovery from mixed wastewater streams. Indeed, Schenk et al. (2009) suggest there are over 30 processes for the recovery of phosphorus from wastewater. One discourse (by way of example) at the small-scale, low-tech end of the sustainable sanitation field, is *ecological sanitation*, or 'ecosan'. Ecosan explicitly stresses the need to 'close the loop' on nutrients, including phosphorus, to ensure sustainable nutrient cycles. Ecological sanitation refers to the containment, sanitization and recycling of human excreta to arable land (EcoSanRes, 2003). While the key objectives are protection of public health and the environment, other important goals are the reduction of water use in sanitation systems and reducing the demand for mineral fertilizers in agriculture by recycling nutrients from human excreta. Human excreta is typically the greatest source of phosphorus discharged from human settlements. While excreta output varies by age, type of diet (such as vegetarian versus meat-based), climate and lifestyle (Esrey et al., 2001), urine it is typically sterile and a readily available source of phosphorus. For example, urine alone can provide more than half the phosphorus required to fertilize cereal crops (Drangert, 1998). There are numerous documented practical local cases of ecological sanitation around the world, including examples from Southern Africa, China, Vietnam, Nepal, and Mexico (Drangert, 1998; Gumbo and Savenije, 2001; Stockholm Environment Institute, 2005; Tilley et al., 2009), and in the developed world from Scandinavia, The Netherlands, Switzerland and Germany (Johansson and Kvarnström, 2005; Münch et al., 2009).

However, *ecological sanitation* has been a minor discourse within the sanitation discourse (Stockholm Environment Institute, 2005) and sanitation in turn is a minor subsector of the water discourse (as indicated above). Further, at the international level, little or no link is made between sanitation and food. The Millennium Development Goals require a focus on both increasing access to sanitation, and halving global hunger (UN, 2005). Yet few projects, let alone discussions, have focused on these interlinkages and coordinated research/studies at the global scale are minimal. Two noteworthy exceptions however, include firstly the recent 'WHO Guidelines for Safe Use of Excreta and Greywater' (2006) which in some sense 'legitimizes' the practice, providing guidelines for any part of the world. Secondly, the Stockholm Environment Institute's '*Sustainable Pathways to Attain the Millennium Development Goals: Assessing the Key Role of Water, Energy and Sanitation'* provides an initial analysis of the commercial value of phosphorus and nitrogen from human excreta in each global region and suggests that the cost of ecosan systems could hypothetically be offset by the commercial value of the phosphorus and nitrogen they yield (Stockholm Environment Institute, 2005). The year 2008 was declared International Year of Sanitation (UN, 2008), and saw the launch of new initiatives, such as the Sustainable Sanitation Alliance, co-founded by two European ecological sanitation research groups (SuSanA, 2008). Despite such advances, more detailed work is needed exploring the barriers and opportunities at the global scale.

At the other end of the spectrum (high-tech, large scale, mixed wastewater), in the more mainstream wastewater sector, implementation of conceptual advances has also occurred, from wastewater *treatment* (for public health) to wastewater *recovery* (for environmental protection) and even *re-use* (for fertilizer value) in some instances. For example, nutrient removal from wastewater treatment plants has developed from chemical processes (in the 1980s) to the biological nutrient removal process (in the 1990s) and most recently to struvite[77] recovery and re-use (Hammond et al., 2007; Ashley, 2009) and other forms (such as ash from incinerated animal meal). Indeed, the 2009 International Conference on Nutrient Recovery from Wastewater Streams acknowledged that:

> *a new "paradigm" is emerging, globally. Commercial marketing of recovered nutrients as "green fertilizers" or recycling of nutrients through biomass production to new outlets, such as bioenergy, is becoming more widespread*[78] (Mavinic et al., 2009).

Today for example there are commercial scale struvite recovery plants operating in Canada (Ostara, 2009; Rahamana et al., 2009) and Japan (Ueno and Fujii, 2001), while commercial operations in The Netherlands sell nutrients sourced from sludge ash to end users (Schipper and Korving, 2009). There have been trials aiming at a marketable fertilizer from municipal sewage in Germany (Adam et al., 2008) and marketable 'biofertilizer' sourced from livestock effluent in Australia (for example, Microfert, 2009). Some small-scale decentralized operations concentrating nutrients are also emerging, such as developments to recover struvite from source-separated urine in Sweden (Ganrot et al., 2009) and Nepal (Tilley et al., 2009).

Advances also differ from country to country (or region to region). For example, recovering nutrients from wastewater streams has been relatively high on the agenda in Sweden for decades relative to many other countries (water quality being a main driver, but also the general need to 'close the loop' on nutrient cycles) (Cordell, 2006). While such emerging initiatives are certainly on the increase around the world, they are far from the mainstream and are generally not operating within an overarching coordinated framework or strategy at a broader scale linked specifically to sustainable nutrient recovery, sanitation and food production. Hence there is still a need to investigate the most appropriate ways of recovering phosphorus in a given context (within a region, country, city) as it is likely that no one social-technical solution will meet all needs. Further, it is important to consider these developments within the context of sustainable sanitation, to ensure they are consistent with preferred future directions and do not, for example, result in technology lock-in. These issues are expanded upon in the recommendations in chapter 8.

5.5 Governance of phosphorus in the global food system

Sections 5.1–5.4 have focused on phosphorus use, management and how phosphorus is conceptualized in society. This section focuses on the governance structures, that is, the *human-activity* system related to phosphorus, and its interrelationship with the *physical* system. The analysis in this section draws from and synthesizes findings and analyses from the stakeholder interviews (*Paper III*), literature review (*Paper I*), oral information and systemic inquiry (*Paper II*).

5.5.1 Institutional architecture of phosphorus: policies, worldviews, actors and roles

This section investigates the institutional structures currently governing global phosphorus resources in relation to food security, to in turn facilitate the investigation of whether or not they are effective, and finally to facilitate a discussion on what could be done to improve the

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[77] Struvite is magnesium ammonium phosphate crystals high in phosphorus. Struvite crystals can form in advanced wastewater treatment processes, permanently clogging pipes and have more recently been intentionally precipitated to prevent buildup and further generate a product that can be used as a slow-release fertilizer (Jaffer, 2002).

[78] Quote from conference homepage http://www.nutrientrecovery2009.com.

governance of phosphorus.

As outlined in section 3.6.3, institutions are deliberately defined broadly in this thesis to include actors and structures and their interrelationships (such as worldviews and roles). The Earth System Governance program[79] articulates institutional architecture as conceptualising:

> *the overarching system of public or private institutions, principles, norms, regulations, decision-making procedures and organisations that are valid or active in the issue area. Architecture can thus be described, in other words as the meta-level of governance* (Biermann et al., 2009, p.27).

This extends the focus of most institutional research beyond single formal institutions and acknowledges that governance can occur at multiple scales, through multiple actors beyond the state and can be both formal and informal. Further, governance architectures can encompass both "*synergies and conflicts*" between: i) different institutional structures, ii) different "*overarching norms and principles that govern these interactions*" and iii) "*norms and principles that run through distinct institutions in the area*" (Biermann et al., 2009, p.27).

Figure 5-14 maps the various institutional elements governing phosphorus at the international level. While various forms of governance structures *related* to phosphorus exist at the international level (as identified in figure 5-14) there are no governance structures explicitly designed to ensure phosphorus availability and accessibility for global food production in the long-term.

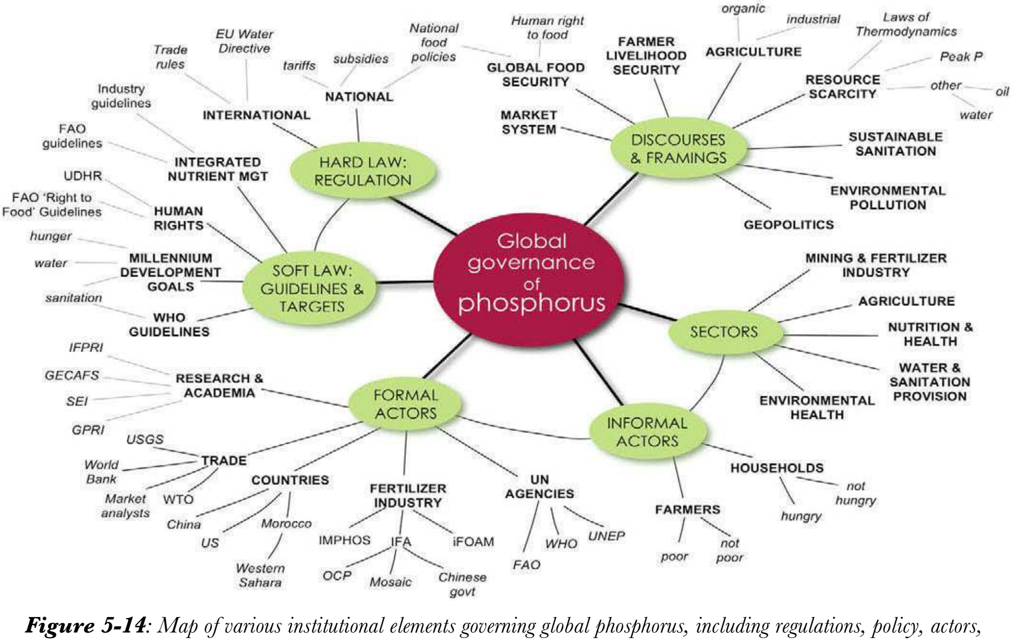

Figure 5-14*: Map of various institutional elements governing global phosphorus, including regulations, policy, actors, sectors and discourses or framings[80]. Refer to 'List of Abbreviations' for explanation of acronyms. Source: created for this research.*

[79] The ESG program superseded the Institutional Dimensions of Global Environmental Change (IDGEC) program within the Earth Systems Science Partnership's (ESSP).

[80] These elements have been identified and drawn from the soft systems analysis in *Paper II*, the stakeholder analysis and stakeholder interviews (in *Paper III* and via the literature review (e.g. *Paper I*).

None of the structures identified in Figure 5-14 address phosphorus scarcity as part of their mandate (as demonstrated in sections 5.1–5.4 and *Paper I*). There are no intentional formal rules or laws in this respect, however phosphorus is indirectly affected by national rules: 1. domestic political boundaries (such as national borders and national food policies); 2, property rights (such as mineral resource exploration and ownership); and 3. international trade rules (for example state tariffs and subsidies, such as China's export tariff on a number of commodities including phosphate and India's subsidies for phosphorus fertilizers).

In this way, there is not so much a conflict between competing explicit management or governance structures of global phosphorus resources for food security. Rather, there is an actual lack, or a situation of 'global non-governance' of this resource for long-term future food security[81]. This was further supported by an analysis of stakeholder interviews (*Paper III*) which suggested a lack of consensus on the problem situation. For example, while all respondents suggested there were no specific international regimes or rules relating to global phosphorus resources, some suggested it wasn't a problem since supply would always meet demand, for example, "*availability…is not an issue. …what we have seen over time is that technology has been able to feed the world*" [UN fertilizer demand expert], while others thought we were on the verge of a geopolitical crisis or food crisis: "*it is a public political liability that puts people at risk with food systems*" [Sanitation and sustainability researcher and practitioner]. The soft systems inquiry (in *Paper II*) revealed key worldviews[82] or discourses prevalent in this context which underpin various stakeholder perspectives (including, but not exclusive to, the respondents interviewed) (see table 5-3).

[81] Biernann et al. (2008) suggest that while such non-governance can occur, it is often largely understudied.

[82] While the German term *Weltanschauung* is used in soft systems methodology and refers to a very personal view or perspective (Checkland and Poulter, 2006), in this context, it is more closely associated with established discourses rather than private and personal views.

Table 5-3*: Five key worldviews with differing goals and implications for future global phosphorus resources (adapted from Paper II).*

Worldview	Significance to the phosphorus problem situation
1. Human right to food	*Goal: hungry people are sufficiently fed.* Global food security means that all people have the right to food as a basic human right. Therefore sufficient food availability (which relies on key natural resources like phosphorus) is a prerequisite.
2. Limiting nutrient in plant growth	*Goal: agricultural soils worldwide are sufficiently fertile to maximize crop yields.* Liebeg's Law dictates that phosphorus is the limiting nutrient in plant growth, therefore farmers need continual inputs of phosphorus fertilizer to ensure high productivity and crop yields.
3. Global market economy	*Goal: demand for phosphate commodities is met by supply.* Rules of free trade and the international market mean that supply will always match demand; resource scarcity is relative as technology will always improve efficiency and processing.
4. Farmer livelihood security	*Goal: farmer fertilizer needs met to obtain crop yields high enough to ensure sufficient livelihood are sustained.* Farmers need fertile soils to contribute to maximising crop yields. Farmer livelihood security means all farmers should have sufficient access to fertilizer markets (or alternative sources like manure).
5. Equity, ethics and corporate social responsibility	*Goal: human rights of individuals and groups are not compromised in obtaining or the use of phosphate sources.* Ethics and the principles of corporate social responsibility (Garriga and Mele, 2004) suggests that industry (and nations) should boycott Moroccan exports of phosphate rock from Western Sahara, until the independence of Western Sahara is achieved and 'ethical' trading of Western Saharan controlled phosphate rock can resume. Equity implies the people of Western Sahara have a right to the phosphate resources on their land.

The above considerations are important because of the way in which the problem is perceived and the worldview behind those perceptions and the power associated with a view, influence the nature of the solution (Rittel and Webber, 1973). Consistent with the notion of 'messy' problems, none of these (world)views are right or wrong; rather, they co-exist. Each set of worldviews and goals has a specific system boundary (drawn either implicitly or explicitly) that includes some actors and entities and excludes or marginalizes others. For example, in the global market economy farmers without purchasing power are marginalized, while in a farmer livelihood security worldview, all farmers are central actors. Further (as introduced in section 5.1), there are numerous societal roles associated with different perceptions of phosphorus with respect to sustainability. Some of these are expanded in table 5-4.

Table 5-4*: Common perceptions of phosphorus in the literature by different roles.*

Role	Common perception of phosphorus
Geologist	11th most abundant element in the earth's crust. Phosphate rock is a non-renewable resource.
Geochemist	A critical biogeochemical cycle, only cycling between lithosphere, biota and hydrosphere (i.e. no atmospheric phase). Phosphorus is an essential element for all life on earth.
Resource economist	An agricultural commodity, a tradable commodity on the international market.
Agronomist	A critical soil nutrient for plant growth, a limiting factor in crop growth.
Farmer	An important fertilizer input (NPK), that contributes to crop growth and hence to higher yields.
Nutritionist	An essential macro-nutrient for human growth. Most deposits found in bones in the form of calcium-phosphate. Phosphorus deficiency is rare in humans.
Geneticist/biologist	Fundamental component of DNA and RNA, critical for transport of energy in the brain (ATP).
Sanitation engineer	A component of sewage (e.g. Total Phosphate (TP) is a standard wastewater indicator); often must be removed to prevent downstream water pollution.
Freshwater ecologist	A component of freshwater, often an environmental pollutant where excess load can lead to eutrophication of waterways. In rare instances, lack of phosphorus in freshwater can lead to oligotrophic waters. The lack of nutrients can limit fish and aquatic populations ability to breed (Anders and Ashley, 2007).

Figure 5-15 maps these institutional roles and dominant framings of phosphorus within each key sector related to the production and use of phosphorus in the food system against the physical phosphorus cycle. This highlights a 'lack of fit' (Young, 2002) between the phosphorus cycle and institutional arrangements. Young here refers to the mismatch between a biogeochemical cycle and the institutional arrangements governing it. In the case of phosphorus, this lack of fit is evident in both spatial and temporal terms, as detailed in the remainder of section 5.5.

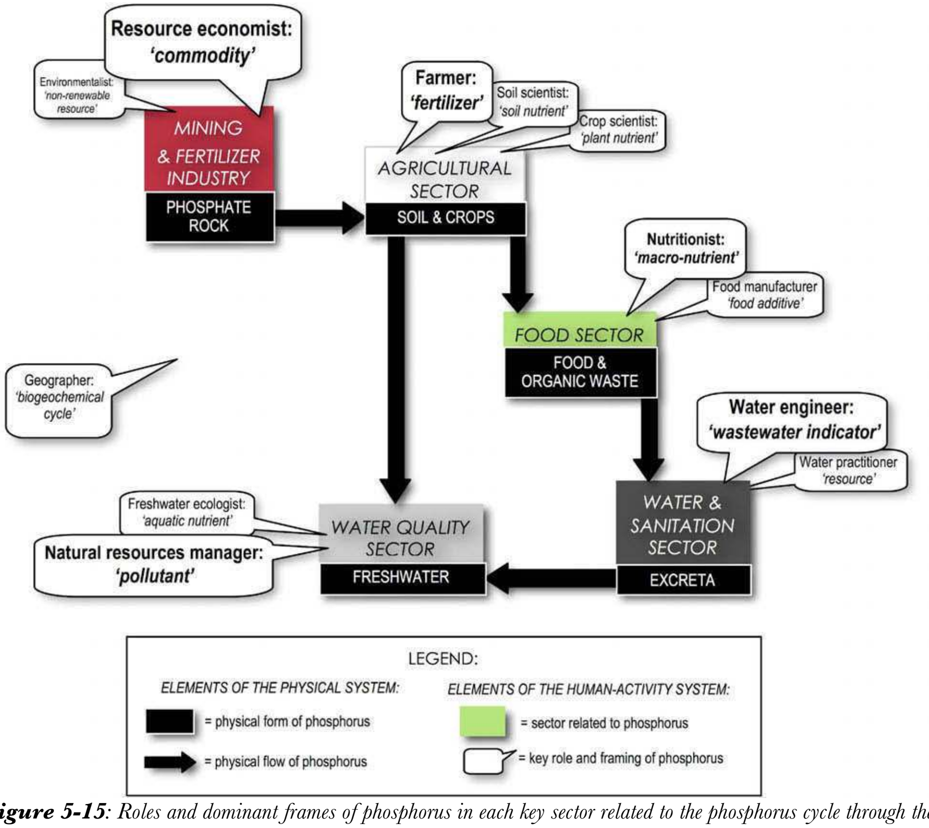

Figure 5-15: *Roles and dominant frames of phosphorus in each key sector related to the phosphorus cycle through the global food production and consumption system. Speech bubbles indicate the way phosphorus is conceptualized in the major sectors. None of these prioritize phosphorus scarcity linked to food security. Source: created for this research.*

Firstly, there is a noticeable fragmentation between the different sectors that phosphorus flows through in the global food production and consumption system (as shown in figure 5-15), some of which are incompatible or inconsistent. For example in the biophysical cycle, the phosphorus we eat comes out in our urine and faeces[83], yet in the institutional arrangements, there is little if no link between stakeholders and sectors around food consumption and sanitation. Young warns "*a regime that ignores what turn out to be significant elements of an ecosystem cannot produce sustainable results*" (Young, 2002, p.12). At the international level, this is exemplified by the recently published WHO comprehensive guidelines on the safe re-use of human excreta (such as urine) in agriculture (WHO, 2006) that have had little impact on the fertilizer strategies of the FAO. The sole staff member responsible for fertilizer demand strategies for farmers at the FAO headquarters only focuses on phosphate rock and not on organic sources of phosphorus, and does not foresee a phosphate rock supply problem in the future (*Paper III*). Additionally, at the time of the stakeholder interviews, there was no staff responsible for organic fertilizers at the FAO headquarters.

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[83] This is the case regardless of whether we are looking at the 'natural' phosphorus cycle, or the 'anthropogenic' (human designed) phosphorus cycle.

To a large extent, the cycle has been fragmented and divided between several different sectors and their associated paradigms. In order for phosphorus to be effectively recovered and re-used as a fertilizer, effective institutional structures linking these sectors would be required. Further, phosphorus would have to be formally perceived as scarce in order to increase its recovery and efficient use.

As suggested in section 5.1, phosphorus is perceived and conceptualized by sectors in many different ways depending in part on the context and sector. Figure 5-15 and Table 5-4 show phosphorus is perceived as an 'environmental pollutant' by freshwater ecologists, or an 'agricultural commodity' by resource economists, and so on. Further, within each of these disciplines, phosphorus scarcity is often not perceived as a priority area, hence it has no institutional home – that is, the discourse has no guardian[84] that can ensure effective governance of phosphorus resources for food security. It is only when the phosphorus cycle is perceived as a whole system which includes connections between entities, that its importance becomes obvious (see *Paper II* and *Paper III*)[85].

5.5.2 Effectiveness of the global governance of phosphorus

How these different actors, roles and worldviews interact and affect phosphorus resources and patterns of use depends in part on power and influence. *Power* here refers to the ability or capacity to make others take specific action or conform to a specific agenda (for example through force), even when it is against the preferred agenda of others. *Influence* is to make others conform without resistance (Biermann et al., 2009). The following figure 5-16 adapts and applies a social-ecological system framework developed by Vatn (2005) to assess how the institutions and actors governing phosphorus (described above) play out in the 'action arena' and the outcomes for the phosphorus resources. The 'action arena' is the space where issues are discussed and negotiated, goods are exchanged and decisions are made (Ostrom, 2006). Outcomes from the action arena are highly influenced by powerful agents. While the framework (Vatn, 2005) was initially designed for local, renewable resources (Vatn per comm.), it has been adapted and applied here to non-renewable phosphate rock at the global scale.[86]

[84] According to soft systems methodology, a guardian monitors the implementation of the transformation in the human activity system, and informs the owner of unintended consequences (see *Paper II* for further explanation).

[85] This fragmentation was also observed in a study of the barriers and opportunities to the re-use of urine in Australia (Cordell, 2006).

[86] The first iteration of this analysis was undertaken in 2007 following consultation with Vatn on the appropriateness of the framework for this context (see Kerschner and Cordell, 2007).

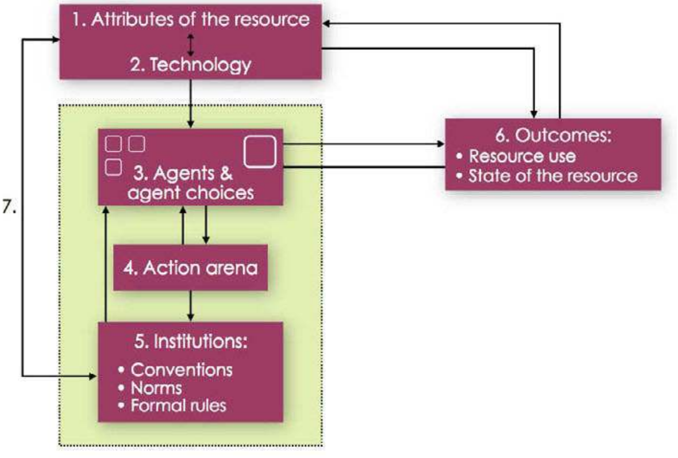

Figure 5-16: *A social-ecological framework for analysing global non-renewable resource use. Seven 'steps' of phases are indicated, including 1. The attributes of the resource, 2. Technological aspects, 3. Agents and agent choices, 4. Action area which is influenced both by powerful actors, and prevailing institutions, 5. Institutions, 6. The outcomes of the choices made by agents on the use and state of the resource, and 7. The relationship between the prevailing institutions and the attributes of the resource. Source: modified from Vatn (2005).*

A stakeholder analysis of power versus interest (Appendix D-2), supplemented by the soft systems inquiry in *Paper II* and an analysis of stakeholder interviews (*Paper III*) revealed that in the absence of any institutions or governance structures explicitly ensuring phosphorus availability and accessibility for future food security and the absence of any specific action arena or formal forum (in step 5, figure 5-16), phosphorus is governed by the dominant prevailing institutional structure (in step 4): the forces of the international market. The conventions within this structure are enacted by the powerful actors (in step 3) (the fertilizer industry, and states – particularly China, US and Morocco) and supported by the dominant worldview of the market economy that supply will always meet demand and scarcity is relative. This prevalence of the market system in the governance of phosphorus resources is further evidenced by the facts that: 1. Only phosphorus *commodities* (that is, phosphate rock and tradable fertilizers, such as DAP, and MAP) are formally included in the system (represented by such structures as the international fertilizer industry, and the FAO's fertilizer demand strategy); 2. Predominantly farmers with *purchasing power* are able to access phosphorus fertilizers; 3. The result of the short-term feedback loop of the 2008 phosphate scarcity was a *price* increase; 4. The short-term price spike attracted unprecedented media, scientific and policy attention to the long-term situation, despite being only indirectly related to these variables; 5. Some national responses at the time of the price increase were: China increased its export *tariff* on phosphate, while Australia undertook a Senate Inquiry into the '*Pricing and supply arrangements in the Australian and global fertiliser market*' (Commonwealth of Australia, 2009).

While the recent price spike in phosphate rock has resulted in some further phosphate rock exploration (Jasinski, 2009) and is likely to trigger further innovations in, and adoption of, phosphorus recovery and efficiency measures, the market alone is not sufficient to manage phosphorus in a sustainable, equitable and timely manner, as will be demonstrated in the following paragraphs. This form of 'regime' is partial, only sufficient to govern part of the system (such as efficiency of trade), and ignores many fundamental relationships and functions of the *whole* system (described below). This is another form of 'lack of fit'. 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, 2002, p.17).

The soft systems inquiry in *Paper II* assessed the current purposeful activity system[87] against five systemic criteria (effectiveness, efficacy, efficiency, ethics and emergence)[88]. The current fragmented and narrow system fails to govern or manage global phosphorus resources in an effective and sustainable way because it does not address key physical and human-activity dimensions and their interactions. In terms of the numbered steps in the institutional framework in figure 5-16 above, the current system fails in the following ways (Note that steps 4 and 5 were outlined earlier).

Attributes of the resource: physical resource scarcity (steps 1+2):

The theory of the market system does not acknowledge the attributes of phosphate rock as a finite non-renewable resource (Kerschner and Cordell, 2007). Rather, the operation of the market is based on the assumption that as a non-renewable resource commodity becomes more scarce, the price will increase, which will in turn trigger new investments and fuel technological innovation (Ayres, 2007). As discussed in section 4.3, this is consistent with the principles of neoclassical economics which suggest that phosphate scarcity is only relative, not absolute in a physical sense, because one scarce resource can simply be replaced by another resource indefinitely. This represents a technological optimism – that new technology will always facilitate this substitution. Neoclassical economics in this instance clashes with the laws of thermodynamics, that suggest low entropy matter (such as high quality phosphate rock) is becoming scarcer in an absolute sense. This neoclassical economic outlook in turn means the market does not accept the concept of peak phosphorus, as the latter is based on the notion of resource scarcity in an absolute or physical sense. This issue is not unique to phosphorus, as was further discussed in section 4.3.

Resource allocation by agents and agents' choices (step 3):

In the current system, the agents (actors) and their choices do not allocate resources equitably across a) geographical space, b) between actors and c) across time:

a. ***Resource allocation across geographical space***. Geologically, phosphate rock is unevenly distributed and deposits are concentrated in only a handful of countries (Jasinski, 2008). Under the market system, countries and their firms are entitled to own the resources within their political boundaries. Despite phosphate being critical to food production in every country and every modern farming system, the overwhelming majority of phosphate rock reserves are currently controlled by just three countries – China, Morocco and the US. The market currently has no mechanisms for equitable distribution of such essential resources (Daly, 1992). Those with purchasing (or military or political) power have the most access (Kerschner and Cordell, 2007).

b. ***Allocation between actors: accessibility to farmers***. Many poor farmers around the world cannot access the phosphate fertilizer market due to low purchasing power or

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[87] A 'purposeful activity system' is defined in soft systems methodology as a system that has a specific goal or purpose which its components are designed to achieve.

[88] 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 a 5th E: 4. Ethics: "Is the whole system and sub-system components ethical?", and a 5. .Emergence: "Does the system exhibit properties of emergence (e.g. synergies) when considered in the context of its' supra-system?".

because the don't have access to credit (IFPRI, 2003; IATP, 2006). Further, in Sub-Saharan Africa, where fertilizers are most needed, phosphate fertilizers can cost farmers two to six times more at the farm gate than it costs European farmers (Runge-Metzger, 1995; Fresco, 2003). The recent price spike and anticipated future price spikes further reduce the purchasing power of poor farmers.

c. ***Allocation across time: intergenerational equity***. Intergenerational equity, a key principle of sustainable development (Friibergh Workshop on Sustainability Science, 2000) means future generations have the right or opportunity to access the same resources as present generations. This is not the case with non-renewable resources that are scarce. However this is not perceived as a problem under the market system which assumes infinite substitutability. That is, scarcity is viewed as being relative and when one resource becomes scarce and hence expensive, market theory argues that it can always be replaced by another cheaper resource. However phosphorus has no substitute in food production, and therefore phosphorus must be available to future generations if societies are to continue.

Long-term time frames (step 6):

We are entering a new and unprecedented era of global environmental change (Biermann, 2006). As we are learning from climate change and global water scarcity, a long-term time frame is essential for understanding, managing and adapting our current system in a timely way. The same applies to global food security and phosphorus resources. Current global phosphate reserves might be depleted in the next 50–100 years, which is very significant for humanity, yet the market system and its actors are structured to operate on short-term timelines of 5–10 years at most. There is a temporal mismatch (or lack of fit) of at least an order of magnitude. The depletion of global phosphorus reserves is also is also below the radar or early warning system of most political decision makers as their timelines are similarly short-term[89]. The typical rate of change of global biophysical systems (in this case, the phosphorus cycle) is too slow to be picked up by the international market – the current institutional arrangements which controls the trade in phosphate. The consequences of this are serious, as the system will eventually reach a tipping point, where the biophysical and technical change is too fast for the 'sluggish' institutional change to keep up with in a timely manner (Kerschner and Cordell, 2007). Young notes that:

> *Institutional arrangements...often change or evolve at a much slower* pace [than biophysical and technological changes]*; major adjustments in many – though by no means all – resource regimes can take years to decades* (Young, 2002, p.22).

Energy intensity and environmental impact (step 6):

Phosphate rock is one of the most highly traded commodities on the international market. Each year around 30 million tonnes of phosphate rock are traded across the globe (IFA, 2006a). Global trade of phosphate commodities is extremely energy intensive and currently relies on cheap fossil fuel energy for mining, processing and particularly ocean freight. With growing concern about fossil fuel scarcity, and the price of oil rising, this current energy intensive process may not be desirable or possible in the future. Mining lower grade rock also decreases the unit output to energy input ratio and generates more waste per unit output. Such

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[89] Although increasingly parties may have long-term goals with respect to the environment. A rare example in the case of phosphorus is the Swedish National Environmental Goal of recirculating 60% of P in sewage back to arable land by 2015 (Swedish Environmental Objectives Council, 2007). However this goal has since been scaled back somewhat as it was seen as too ambitious to realistically achieve in the time frame.

environmental impacts are still externalities and therefore not reflected in the market price.

Irreversibility and tipping points (step 6):

Continual anthropogenic pressure on a resource or ecological system can push the system past a 'tipping point' to a new, irreversible state. This is the great concern with climate change or loss of biodiversity (Stockholm Resilience Centre, 2007). In the case of phosphorus, a tipping point is peak phosphorus, after which supply will be increasingly unable to meet demand. Food riots and farmer suicides are examples of negative social consequences of the short-term imbalance between supply and demand for food and fertilizers. Dead zones are an example of a negative ecological consequence[90] (World Resources Institute, 2008).

Accountability and data transparency (step 7):

As discussed in section 3.4.2, there is very little data or analysis regarding supply and demand of phosphorus resources for future food production (*Paper I*). Data which does exist, is typically generated and owned by the mining and fertilizer industry[91]. While some basic data is publicly available, such as US Geological Survey data on global phosphate reserves, its reliability is questionable and most data is held by industry and considered 'commercial in confidence'. Knowledge production itself is also not independent (often undertaken by mining industry) and assumptions can influence findings, such as how long current global phosphate reserves will last. Similarly, there is no publicly available detailed and reliable timeseries commodity price data for phosphate rock or phosphate fertilizers. Some commercial data is available but only at a very high cost[92], despite the fact that farmers and national policymakers have a strong need and right to know about the short- and long-term future of a resource critical to their livelihoods and national food security. The market does not ensure knowledge production is participatory, equitable, transparent or sufficient.

Adaptive capacity (step 7):

While commodity price rises tend to trigger new exploration, alternatives and technological advances in the short term, in the longer term the market is not responsive enough to changes such as global environmental change. This is partly attributed to the 'short-termness' of industry and the market, a lack of internalized ecological impacts in the market price and a lack of independent early warning systems that monitor the phosphorus for food situation with subsequent feedback mechanisms to the system to adapt in a timely way. The recent fertilizer price and supply crisis was not foreseen by most of the world's farmers or policy makers. Most national and international governmental organisations have not monitored phosphate rock often because it is not seen as a commodity of significance (*Paper V*). World Bank commodity price data (both 'real' and projected) for phosphate rock completely missed the recent price spike[93] (World Bank, 2008). There is currently little institutional diversity that could allow the system to adapt as the market is the main institution governing phosphorus resources. While the current institutional arrangements pertaining to global phosphorus resources, has little adaptive capacity, there is a growing interest generally in "*devising more flexible institutions, capable*

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[90] Where excess nutrient runoff (phosphorus and nitrogen) from agriculture and sewage effluent result in the death of entire aquatic ecosystems which can be irrecoverable.

[91] In Australia, for example, the national government's geological centre, 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 (GeoScience staff, pers comm. 30/01/08).

[92] for example, a subscription to the comprehensive Fertilizer Week statistics costs 2850 Euros (http://www.cruonline.crugroup.com/FertilizersChemicals/FertilizerWeek/tabid/177/Default.aspx)

[93] The forecasts have since been updated online.

of monitoring and adjusting quickly to changing ecological conditions (Young, 2002, p.23)[94]. This is consistent with the notion of complex systems (as described in section 3.2 and *Paper II*) that require monitoring, and feedback and control loops in order to self-reorganize.

5.6 A changing situation: a paradigm shift underway?

While the implications of phosphorus scarcity for future food production has been largely ignored in the dominant discourses of global food security, global environmental change and resource scarcity for decades or even centuries (as argued in chapter 4), the year 2008 witnessed dramatic changes to the global phosphorus and food security context[95].

Most notably perhaps was that the price of phosphate rock escalated from US$50/tonne to over US$400/tonne as indicated in figure 5-17 (World Bank, 2009). As discussed in *Paper I*, this was thought to be due to a number of factors, including increasing demand for phosphorus fertilizers due to the increasing popularity of meat- and dairy-based diets, especially in growing economies like China and India, and the expansion of the biofuel industry. Increasing concern about oil scarcity and climate change led to the recent sharp increase in biofuel production. The biofuel industry competes with food production for grains and productive land and also for phosphorus fertilizers. The International Fertilizer Industry Association also suggested the price increase was due to under investment in new capacity (creating a short-term scarcity due to the time lag between increased demand and commercialisation of new phosphate rock plants) and exchange rates (resulting in the value of the US dollar pushing up quoted prices) (IFA, 2008). Nitrogen and potassium fertilizers experienced similar price spikes. As noted earlier, China increased its export tariff on phosphate rock to 135% to protect domestic fertilizer production, which essentially prevented exports overnight (Fertilizer Week, 2008).

[94] Indeed, the recent establishment of the Stockholm Resilience Centre is an indication of this emerging awareness.

[95] Section 3.4.1 on data sources describes how data on these 'changes' were collected.

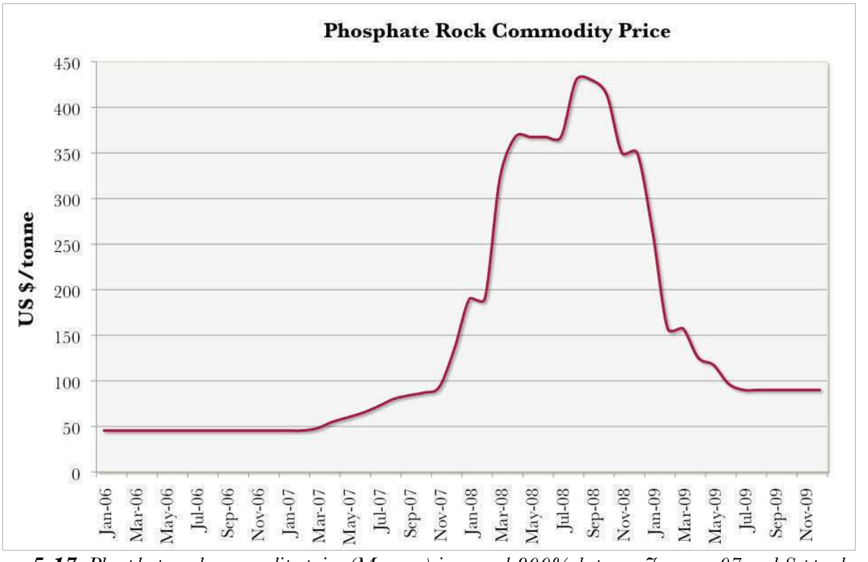

***Figure 5-17**: Phosphate rock commodity price (Morocco) increased 800% between January 07 and September 08. Data: (Minemakers Limited, 2008; World Bank, 2009).*

In the same period, the price of oil rose to over $140/barrel, the demand for biofuel crops surged and discussions of peak oil increased (BBC News, 2008). There were regular reports in the media of the global food crisis, increased food insecurity and indeed food riots (Bombay News, 2008; FAO, 2008c). The UN fertilizer demand expert[96] reassured the public following the escalating fertilizer prices in early 2008, *"we expect fertilizer supply to grow sufficiently to meet higher consumption"* (FAO, 2008b)[97].

The international and national mainstream media began reporting on global phosphorus depletion with headlines such as "*Warning of World Phosphate Shortage*" and "*Scientists warn of lack of vital phosphorus as biofuels raise demand*"[98] (Lewis, 2008; Warren, 2008) and the term 'peak phosphorus' shifted from receiving negligible citings to over 2500 Google hits by mid-2008. Institutional, industry and governmental documents and websites began referring to global phosphorus scarcity (NSW Department of Primary Industries, 2008; Scottish Ministry, 2008; CEEP, 2009; ETC, 2009; European Commission, 2009a)[99]. The increase in informal Internet activity (such as blogging) as a means of real-time global communication may have also accelerated a) informal dialogue on phosphorus scarcity[100]; and b) the increased number of Google-hits on keywords.

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[96] As noted earlier, this is the only international position within the UN system responsible for fertilizer demand strategies, hence its significance in this context.

[97] However the UN fertilizer demand expert retired from this position in December 2008. As at July 2009 the position had not been filled.

[98] This is not entirely an observation as I have been involved in a number of these media items and hence have influenced the situation. Details of this participant observation are provided in Chapter 7.

[99] As above.

[100] Publicly available internet blogs were monitored for keywords as described in section 3.4.1, however these informal channels were not actively used as data in the analysis, but rather for observational purposes.

In addition to media, numerous popular science, academic and policy discussion papers have emerged that raise concerns about impending phosphorus scarcity (Rosmarin et al, 2009; Smit et al, 2009; Vaccari, 2009)[101]. In the following period (November 2008–July2009), the price of oil and all major fertilizers crashed and the global financial crisis set in. Farmers were holding off purchasing fertilizers in the hope that prices would come down (Heffer and Prud'homme, 2009). The price of phosphate rock dropped, though still remains several times higher that the average price prior to the 2008 price spike (CRU Group, 2009). An unprecedented one billion people (one-sixth of humanity) were reported hungry in 2009, up from 840 million in previous years, as a result of the global economic crisis (FAO, 2009).

As of 1 January 2009, China dropped the export tariff, however the EU and US took China to the WTO for anti-competitive behavior regarding phosphate and another globally significant commodities (Euronews, 2009; European Commission, 2009b).

These events demonstrate a significant change in the level of public discussion and concern about global phosphorus scarcity (and peak phosphorus). However according to Arts's 'discursive institutional' framework that assesses how new ideas or discourses become institutionalized or normalized (Arts and Buizer, 2008), this would be considered very shallow institutionalism, as no policies have yet changed due to these new discussions. Arts suggests 'deep institutionalism' would require a change not just of framing, but also policy, rules and power structures. While no substantial changes in phosphorus-related actors, rules or power balances have been observed at the international level[102] a recent EU invitation to tender on 'Sustainable Use of Phosphorus' may be a sign of institutional change to come (European Commission, 2009c).

This chapter has built the main argument of this thesis (supported by the analysis and findings in *Papers I - V*) and building from chapters 4 that phosphorus is critical, requires appropriate management to ensure short and long-term food security, yet currently management is far from sustainable. The following chapter 6 then synthesizes the argument and further reconceptualized the nature of the problem in a holistic way, and provides conceptual guidance for what would be required to achieve a sustainable situation.

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[101] Again, this doctoral research has in part informed these publications.

[102] Perhaps an exception is the launch of the Global Phosphorus Research Initiative (see: www.phosphorusfutures.net) as an outcome of this doctoral research, and the formation of the Dutch Nutrient Flow Task Group (see: phosphorus.global-connections.nl) (which has in part been influenced by this doctoral research). These would be described by Arts as an 'advocacy coalition'.

CHAPTER 6: FROM PHOSPHORUS SCARCITY TO SECURITY: SYNTHESIS OF FINDINGS

This section takes the argument built in chapters 4 and 5 (and *Papers I - V*) and synthesizes the analysis and findings[103], identifying and integrating multiple dimensions of phosphorus scarcity from a sustainability perspective. From this, a new paradigm, *phosphorus security*, is proposed to address the many dimensions of phosphorus scarcity. This provides conceptual guidance for the more concrete 'real world' final conclusions and recommendations (chapter 8) which conclude the arguments of this thesis.

6.1 Five dimensions of phosphorus scarcity

Since the chemical discovery of phosphorus in 1669, our understanding of the element has undergone several key transformations: from its light-bearing and flammable properties in the 17th century, to its key role in crop growth by the 19th century (and later in the Green Revolution) to its role in the eutrophication of many of the world's water bodies in the 20th century. The 21st century is now witness to yet another globally significant understanding: phosphorus scarcity.

The concept of global phosphorus scarcity linked to food security is an embryonic discourse in the mainstream debates on food security and global change (despite early warnings of phosphorus being 'life's bottleneck' by prominent scientists such as Isaac Asimov)[104]. However there is still little consensus among key stakeholders (and indeed between scientists) on whether dwindling phosphorus supplies will actually threaten future food security. Those who argue phosphorus will never 'run out' per se are not 'wrong': phosphorus is an abundant element in the earth's crust that has no atmospheric phase, and thus it transfers between the lithosphere, biosphere and hydrosphere. Phosphorus cannot be created or destroyed. However, high quality phosphate rock is becoming increasingly scarce. The phosphorus in phosphate rock – the essential ingredient in today's fertilizers – cycles naturally between the lithosphere and hydrosphere in cycles of around 10–15 million years, while the anthropogenic food system mobilizes phosphorus from the lithosphere (phosphate rock) to hydrosphere (lakes, rivers, oceans) at rates of 'days to years'. Once those same phosphorus molecules reach the hydrosphere, they are dissipated to such a large extent that they are virtually unrecoverable from an energetic point of view for the next few million years (until they have settled to the bottom of the sea bed, risen due to tectonic uplift and finally eroded down from the mountains). Therefore, the quality of remaining phosphate rock reserves (measured as % P concentration, presence of contaminants) is decreasing. Thus, concentrated and easily accessible sources of phosphorus such as high grade phosphate rock are physically scarce in a human timeline. This situation is however far from simple, and the following framing aims to unravel and reconceptualize some of the 'mess'.

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[103] Hence all references can be found in the specific chapters rather than in this synthesis.

[104] As noted in section 5.6, as little as two years ago, concepts of global phosphorus scarcity and peak phosphorus were virtually non-existent in the media, policy and academic circles.

Phosphorus scarcity essentially occurs when the rate of supply cannot meet the rate of demand within a defined temporal and geographical boundary. There will always be a demand for phosphorus to a greater or lesser extent because there is no substitute for phosphorus: it is a fundamental element for the growth of all living things, including bacteria, plants and animals. While fertilizer demand has been stabilizing in the developed world due to previous decades of over application, the demand in emerging and developing economies like China, India and Brazil is anticipated to soar over the coming decades. Unlike oil, phosphorus cannot be substituted for when scarce. When mining and processing of phosphate rock became commonplace after World War II, there were largely no supply concerns as phosphate rock was thought to be a limitless and easy source of highly concentrated phosphorus. However the most highly accessible and high quality sources were mined first, and today we know we are left with lower grade reserves that are harder to access, are contaminated with more heavy metals, and contain lower concentrations of phosphorus.

Further, the production of phosphate rock will eventually reach a peak due to these economic constraints of accessing more difficult and lower quality layers. Peak phosphorus is likely to occur before 2035 according to the analysis in this thesis based on industry data[105]. The most common response to resource scarcity has been increased commodity price, triggering increased exploration and some technological development. However this will only result in mining lower grade reserves with increasing energy, economic and environmental costs. Further, it is argued that increasing technological efficiency may marginally delay the peak, but this will only act to steepen the down slope after the peak.

The environmental costs of phosphate rock mining extend from the mine down the entire food chain. These costs include: the generation of an ongoing stream of phosphogypsum by-product which must be stockpiled due to its radioactivity; the presence of heavy metals such as cadmium which must be removed due to their toxicity to soils and humans; the energy required not just to mine and process phosphate rock into fertilizers, but to transport phosphorus from the mine to the farm gate; and finally the leakage from agriculture which can lead to severe eutrophication problems.

Addressing phosphorus in the context of sustainability means consciously taking a broad perspective that considers (and indeed integrates) social and economic dimensions in addition to environmental sustainability. As put forward in section 4.3, scarcity occurs at the interlinkage between the resource and human activity and can be defined by a number of factors. Phosphorus scarcity is by no means only concerned with *physical* scarcity of high-grade and accessible phosphate rock; it is also related to economic, managerial, institutional and geopolitical scarcity (described in table 6-1 and the text below).

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[105] Section 5.2 and *Paper I* discuss uncertainties related to this.

Table 6-1: *Five dimensions of phosphorus scarcity: physical, economic, managerial, institutional and geopolitical.*

Dimension of scarcity	Relevance to phosphorus
Physical scarcity	Physical *availability* of phosphorus is constrained, such as the lowering availability of the world's high quality phosphate rock reserves.
Economic scarcity	Lack of *access* to phosphorus, due to constraints in financial capacity (e.g. farmer purchasing power, investments in new resources) or constraints in labor and time capacity to source phosphorus.
Managerial scarcity	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).
Institutional scarcity	Scarcity resulting from a lack of appropriate and effective institutional structures to ensure phosphorus supply will meet demand both in the short and long term, for all users.
(Geo)political scarcity	Availability or access to phosphorus resources is restricted due to political or geopolitical circumstances such as monopolies or oligopolies controlled by governments or corporations.

Economic (or financial) phosphorus scarcity can and does occur when phosphorus users (mainly farmers) cannot access phosphorus sources, usually due to a lack of purchasing power or an inability to access credit. The current demand for phosphorus only represents those users who have the capital enabling them to procure phosphate rock or fertilizers. In order to maximize crop yields globally to feed 9 billion mouths by 2050, there will need to be a boost soil fertility, particularly in areas with phosphorus-deficient soils and a high rate of food insecurity like Sub-Saharan Africa. This means ensuring farmer access to phosphorus. Indeed, the recent price spike resulted in many farmers around the world not purchasing fertilizers which in turn will effect current crop yields, farmer livelihoods and soil fertility for subsequent crop production. Governments from Australia to India urged farmers to apply fertilizers. Financial scarcity on the supply side can occur when investments in new capacity (such as phosphate rock mines) and commercial production do not keep up with market demand for the resource (time lags can be 5–10 years). This was thought to be a significant factor leading to the 2008 short-term phosphate rock scarcity situation.

The scarcity of *management* of phosphorus is highly prevalent throughout the food production and consumption system. For example, currently 80% of the phosphorus mined for food production never reaches the food the world eats due to substantial inefficiencies in the entire food production and consumption system. Phosphorus is lost during mining and processing, transport, fertilizer application, food processing and retail, food preparation and consumption. Many of these inefficiencies are at the same time resulting in pollution of waterways (from agricultural runoff and sewage effluent) which are environmentally damaging and costly to society.

In relation to *institutional* scarcity, there is a substantial lack of policies and actors explicitly governing global phosphorus resources to ensure availability and accessibility for food security, both in the short- and long-term. Further, there are no structures for monitoring and evaluating the situation and no effective feedback loop designed to correct the system. The significance of this was highlighted in 2008 when the short-term demand temporarily outstripped supply capacity, resulting in an unprecedented price spike, trade protection barriers, fertilizer rationing and even riots in some instances. The lack of effective global governance is compounded by a lack of stakeholder consensus on the issues and institutional fragmentation which means that sustainable governance of phosphorus has no obvious home in any sector. Phosphorus is by default governed by the market system, which is only sufficient for a very narrowly defined system (including efficiency of trade), but is not sufficient to adequately address the much broader sustainability implications, such as the need for access to phosphorus for all farmers, the finite nature of phosphate rock resources and the long-term situation, as depicted in figure 6-1 below.

Finally, the *geopolitical* scarcity surrounding phosphorus resources could be as significant as the geopolitical scarcity surrounding oil resources. For example, while all farmers need access to phosphorus, phosphate rock reserves are controlled by a handful of countries, including China, the US and Morocco. In 2008 China imposed a 135% export tariff to secure domestic supply, a move which essentially halted exports from the region overnight, and by 2009 the US and EU had gone to the WTO claiming China was exhibiting anti-competitive behavior. The US is expected to deplete its own high-grade reserves in the coming decades and increasingly imports rock phosphate from Morocco. However Morocco continues to occupy Western Sahara and controls that region's reserves, in defiance of UN resolutions.

In the past three years, global phosphorus scarcity has shifted from being a subject which was hardly ever mentioned in the dominant discourses on global food security to one that is increasingly being discussed. Whilst this increased awareness or discussion does not constitute 'deep' institutional change, in that no policies or actions have yet changed as a result, the first step is to raise awareness, trigger discussion and debate on the nature of the problem situation, and then how best to address it.

Critical systems thinking asks the analyst to critically reflect on how system boundaries are constructed (whether intentionally or unintentionally), because they are laden with value judgements. For example, which *actors* are included or excluded from the system, *what* entities are considered? And *who* decides on the system boundary? (Midgley, 1992b). In the case of governing phosphorus, it is clear that there is a lack of fit with the physical system and the current system boundary is narrowly defined, predominantly including the actors from the mining and agricultural sectors (that is, the fertilizer industry and those farmers who can access fertilizer markets), with phosphate rock as the main entity and eutrophication as the main environmental problem.

However a sustainable situation requires a substantial broadening of the system boundary to more equally include: other actors (such as poor farmers); the *entire* food production and consumption system (beyond mining, fertilizer production and application in agriculture); other phosphorus sources (such as human excreta and food waste); other environmental issues (such as physical scarcity); and finally other time frames (long-term in addition to short-term). Figure 6-1 conceptualizes the current narrow system boundary, and a wider system boundary required for sustainable phosphorus futures[106]. There is also a need to define *who* will manage

[106] This figure should be interpreted as indicating those entities that are largely included or largely excluded relative to one another, rather than an absolute inclusion or absolute exclusion. There are, for example, programs that address poor farmers' access to fertilizers, and similarly some human excreta is indeed used a source of phosphorus fertilizer. However these are far

this new system boundary, that is, which actors will be responsible for redefining and governing global phosphorus resources for food security in a sustainable manner.

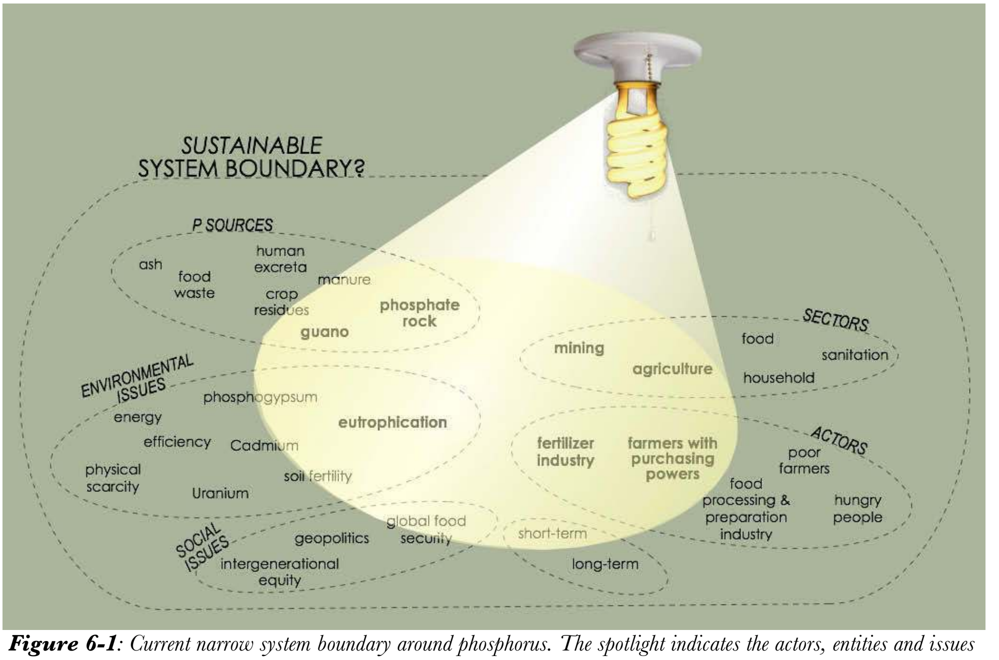

***Figure 6-1**: Current narrow system boundary around phosphorus. The spotlight indicates the actors, entities and issues that are largely currently included in the governance of phosphorus, predominantly due to the market system, and those that are largely marginalized or ignored. A more sustainable situation would require the system boundary to be redrawn more broadly to equally include other important actors (such as poor farmers), environmental issues (such as physical scarcity), other sources of phosphorus (such as excreta or food waste) and longer time frames. Source: created for this research.*

6.2 What we know, what we guess and what we don't know[107]

In order to create change towards a preferred future, certain critical independent and trustworthy knowledge sets are required. Consensus is at least needed regarding the existence of a problematical situation, the need to change the current system and roughly the key nature of the challenges.

This thesis has addressed several key knowledge gaps and advanced understanding of others during a period of rapid change. However, there is still a scarcity of data and analysis, and hence there are still many uncertainties. There are things we know with a greater level of certainty and societal and scientific consensus[108], there are things we guess and there are things

from mainstream.

[107] The heading structure 'What we know, guess and don't know' comes from Louise Fresco's 2003 keynote address to the IFA/FAO Agricultural Conference when she was Assistant Director-General of the FAO (Fresco, 2003).

[108] It is important to distinguish consensus from truth or 'objectivity'. Midgley (2003) reminds us of Foucault's notion that consensus "can be the product of cultural construction".

we don't know. Further, there are things we don't even know we don't know; that is, there is persistent uncertainty. The following sections summarize these knowledge sets on a spectrum from high to low levels of uncertainty and consensus.

1. What we know (high level of certainty and consensus)

Following this doctoral research and a period of rapid change in the field, the following summarizes what is currently known, and agreed upon, to a greater or lesser extent.

Phosphorus and food production: Phosphorus is essential for food production. Therefore, there will always be a demand for phosphorus for the foreseeable future. As an element, phosphorus cannot be created or destroyed. Phosphorus is abundant in the earth's crust, including the soil, but plant-available phosphorus is limited to phosphorus in soil solution.

Fertilizer production from phosphate rock: Most phosphorus demand today is met by mining and processing phosphate rock into commercial fertilizers like DAP, MAP and TSP. Phosphate rock is a non-renewable resource and high-grade reserves will not last forever. The quality of the phosphate rock sold on the international market is decreasing for example, the concentrations of phosphorus in the rock are decreasing). The presence of heavy metals like cadmium is increasing in remaining phosphate rock reserves and must be removed as it is too toxic to be put in soils. Economic reserves and deposits are geographically concentrated in just a few parts of the world. High-grade deposits exist in nodes on the seabed. Energy will be a factor which constrains mining and distribution in the future. Production costs are increasing (due to lower grades, the increasing presence of heavy metals, and increased energy costs).

Phosphorus pollution: In addition to the environmental problems of phosphorus production described above, eutrophication continues to be a global environmental problem, requiring multi-sectoral approach to management.

Demand for phosphorus: 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. Diets in emerging economies like China and India are increasingly trending towards increased meat and dairy consumption, which results in increased overall demand for phosphorus, as meat requires far more phosphorus and other inputs to produce than other food. 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.

Inefficiencies in the system: Crops take up only a small fraction of the phosphorus applied in fertilizers. Phosphorus losses from agricultural fields (and effluent discharges) are leading to eutrophication and water pollution in many parts of the world.

The short-term situation: The price spike of phosphate rock in 2008 led to farmer riots and formal investigations in various parts of the world (such as the Senate Inquiry in Australia). The price dropped in late 2008 in part due to the financial crisis and farmers holding back on purchasing fertilizers. The global financial crisis pushed global food insecurity to an unprecedented level, with over one billion people hungry.

Governance of phosphorus resources: There are no explicit international policies or organisations with the role of ensuring long-term access to phosphorus sources for food production. There is very little publicly available and reliable information and data on phosphate rock and other sources of phosphorus. The fertilizer industry does not disclose all significant information to the public (or even to governments). Market analysts provides some information at a cost which makes it inaccessible to most researchers and farmers.

2. What we guess (moderate degree of uncertainty and consensus)

The following summarizes issues about which not enough is known, or about which there is little consensus.

Fertilizer production from phosphate rock: there is still substantial uncertainty regarding reported current reserves (for example how accurate China's self-reporting of reserves is, given their estimate dropped 3 000 million tonnes between the 2008 and 2009 reporting years. Further, the assumptions used for reporting what is 'economically and technically feasible' vary from country to country. It is also unclear precisely what potential future reserves exist. That is, we don't know how much more could be discovered and how long new deposits would last. There is substantial uncertainty and lack of consensus regarding the extent to which new technology will 'fix' the problem. The peak phosphorus timeline presented in this thesis is contested both by industry, which views it as being too 'doom and gloom', and by some peak oil scientists who propose the peak occurred in 1989 and therefore argue that 2030–2035 is too conservative an estimate. The risk of exposure to radioactivity levels from the decay of uranium in crushed rock is a largely under-discussed concern, while the radioactivity risk associated with storage and use of phosphogypsum by-product is disputed. While industry suggests the energy consumption in phosphorus fertilizer production is negligible relative to nitrogen fertilizers, the total energy consumed due to phosphorus use, from source to farm gate and beyond, is unclear.

Despite the uncertainty, there is at least now consensus that more reliable data and analysis of phosphate rock is required. For such analysis to be considered trustworthy and reliable by multiple stakeholder groups, assumptions should be transparent, data made public and analysis independent.

Demand for phosphorus: The long-term demand for food, and hence the long-term phosphorus fertilizer demand, is still unclear. However, the analysis in this thesis suggests a likely increase in the long term. The analysis also suggests that meeting the long-term future phosphorus demand (for food production) will likely require a substantial reduction in the demand for phosphorus (through changing diets, food chain efficiency and increased recovery).

Inefficiencies in the system: There are substantial inefficiencies throughout the food system, related to phosphorus production and use, and there is a lack of available data on: food waste; phosphorus content in phosphogypsum and other by-products during the mining, refining and fertilizer production processes.

Recovery and reuse of phosphorus: While relatively detailed data exists for the annual consumption of phosphate fertilizers based on phosphate rock, the quantity of organic 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.

3. What we don't know (high degree of uncertainty and consensus)

There are still many unanswered questions that have not yet been explored, such as: What impact will demand for biofuel (from virgin crops, algae, biowaste or other sources) have on the demand for phosphorus[109], and on phosphorus pollution? What impact will climate change have on the demand and use of phosphorus resources? What impact will climate change *policies* have on phosphorus use patterns? What if lithium-ion car batteries, each containing 46-60 kilograms phosphate are brought into circulation? Will there be more phosphorus price spikes or troughs? What will the full impact of the global economic crisis be? How long will the occupation of Western Sahara and its reserves continue? How will the control of phosphate rock reserves play out? How can phosphorus be safely and economically extracted from the phosphogysum by-product without risking radiation exposure and high energy use? What are the most sustainable ways to reduce the demand for phosphorus and to recover and efficiently re-use phosphorus? And finally, *who* is responsible for governing and coordinating the long-term management of phosphorus for food security?

4. What we don't know we don't know (persistent uncertainty)

Finally, 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 (for example, the global financial crisis in 2009 and its effect on phosphorus use was largely unforeseen). 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.

6.3 Phosphorus security

Whilst many new global networks and paradigms are emerging or evolving to tackle sustainability problems (such as resilience, transdisciplinarity, earth system governance, systems science, and sustainability science), many of the underlying principles and messages are unified. That is, they all suggest that a long-term, integrated, interdisciplinary approach is required, and that systems be redesigned to consider new global challenges and designed to be flexible and adaptable both to relatively predictable changes and to changes which are unforeseeable.

Despite the presence of uncertainty and some degree of lack of consensus about the probable future of phosphorus, the underlying problem will still persist. What is clear is that unless we intentionally change the way we source and use phosphorus, we will end up in a 'hard-landing' situation with increased phosphorus scarcity and phosphorus pollution, further price fluctuations (affecting poor farmers first) and increasing energy consumption. In order to achieve a preferred 'soft-landing' outcome (figure 6-2), 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.

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109 However some very recent studies have emerged which address the possible impacts of biofuel demand, including Horn & Satorius (2009) and Smit et al (2009).

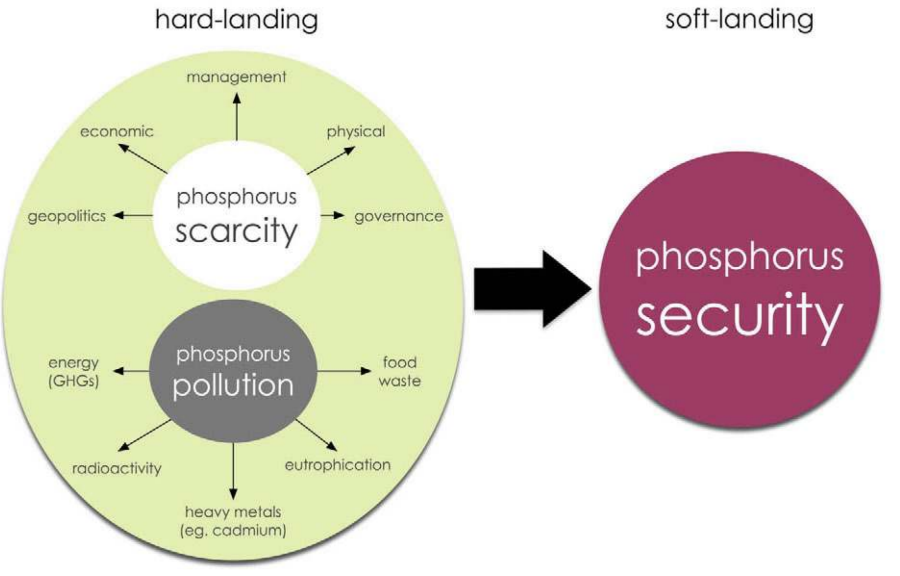

Figure 6-2*: From phosphorus scarcity and pollution (a hard-landing) to phosphorus security (a soft-landing). Source: created for this research.*

There is a strong need for a new global goal that can address the disparate challenges outlined in this thesis. Global food security, water security and energy security are all relatively accepted discourses that encompass multiple dimensions. The goal of achieving phosphorus security is proposed in this thesis in a manner which encompasses the multiple sustainable dimensions of the phosphorus issue. A proposed definition is:

> ***Phosphorus security*** *ensures that all the world's farmers have access to sufficient phosphorus in the short and long term to grow enough food to feed a growing world population, while ensuring farmer livelihoods and minimising detrimental environmental and social impacts.*

A central aspect of phosphorus security will be meeting long-term phosphorus demand for food production. Following the findings from the scenarios analysis in *Paper IV*, this is likely to require an integrated approach that includes a) a high recovery rate of all sources of phosphorus from the food chain (crop residues, manure, food waste, human excreta) and new sources 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 6-3 synthesizes findings from the preferred future scenario analysis. While probable, possible and preferred scenarios were analyzed (in *Paper IV*), figure 6-3 presents a preferred scenario. Due to the substantial and growing gap between business-as-usual demand and supply from current sources, measures to decrease the demand (such as approaches to reduce current inefficiencies) were first developed. In this scenario, 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.

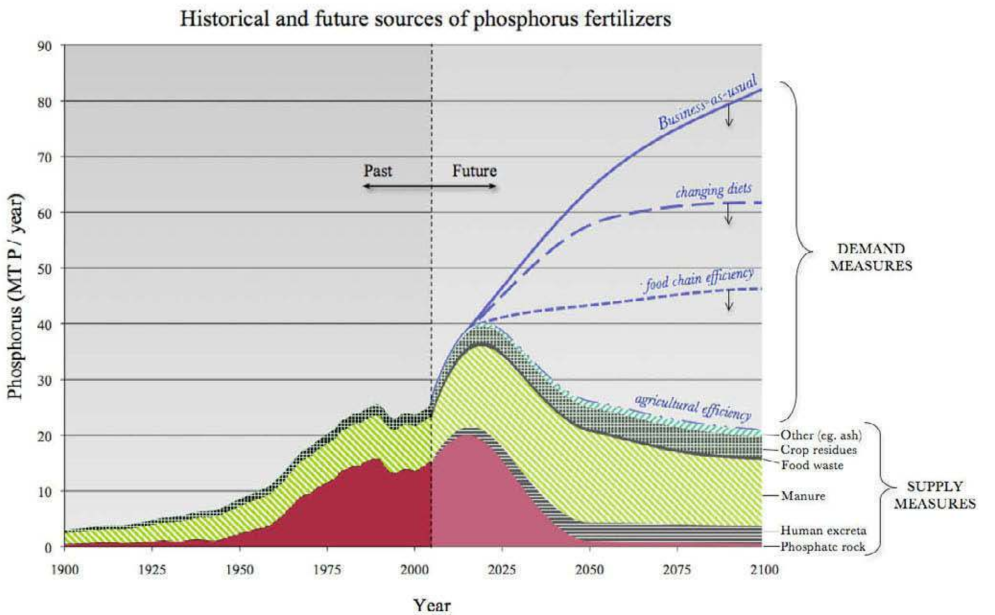

***Figure 6-3**: Meeting future phosphorus security through a range of demand and supply-side measures. Source: created for this research (Paper IV).*

Importantly, this analysis (see *Paper IV*), 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).

Different sources of phosphorus have different advantages and drawbacks. Indeed, there has often been an oversimplified debate over 'synthetic' fertilizers versus 'organic'. Some observers contend that all fertilizers are 'bad' due to their impact on the environment. The distinction between 'synthetic' and organic' fertilizers is often misleading and oversimplified, because there are advantages and drawbacks of different types (Appendix A-3 compares the attributes of mineral and organic fertilizers). More appropriate criteria for the 'sustainable' use of fertilizers are required, including an examination of such factors as life-cycle energy consumption, other resource consumption, accessibility, availability, and pollution. How the fertilizers are applied in the field is also important and can have environmental and socio-economic consequences. A framework for assessing different sources is presented in *Paper IV*. While use of organic sources of phosphorus like manure and crop residues is somewhat widespread, phosphate rock is predominantly the source of phosphate fertilizers today. Indeed the only phosphate fertilizer producers represented by peak international fertilizer industry bodies are those who manufacture phosphate rock-based fertilizers (see *Papers III* and *Paper V*). However, most of these bodies (including the IFA and the FAO) formally promote 'Integrated Nutrient Management' as outlined in *Paper IV*. And more recently, industry has espoused the "four R's" which promote improved fertilizer management practices through *source, rate, time* and *place*

(IFA, 2009b).

Increasingly it is being understood that in an era of unprecedented global environmental change it is no longer appropriate to take a single-sector or single-discipline approach to complex sustainability problems in the policy (practical) or research (theoretical) realms. Rather, an integrated or systemic approach is required. Söderbaum calls for 'paradigm co-existence' (Söderbaum, 2006), in which more fitting and flexible ideologies can co-exist to ensure more relevant governance for sustainable futures. A key feature of the phosphorus security goal proposed here is that it addresses not just ecological goals (such as soil fertility) or social goals (such as farmer livelihoods), but includes and integrates all key sustainability objectives in the one framework. Figure 6-4 conceptualizes the goal of phosphorus security as a series of 11 interrelated sustainability criteria. These sustainability criteria can then be used to address the complex and interconnected network of current challenges related to phosphorus scarcity (that have been presented and analyzed throughout this thesis)[110].

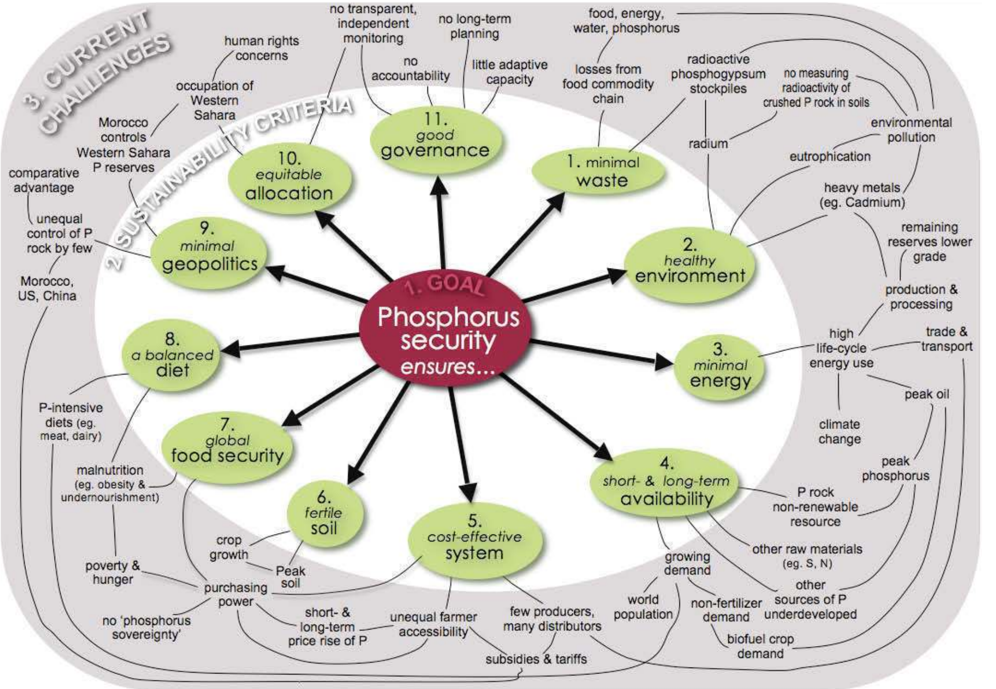

Figure 6-4. Conceptualising the goal of phosphorus security (1), as a set of 11sustainability criteria (2). Such criteria can address the complex web of current challenges (3) associated with phosphorus scarcity (depicted in the outer shaded area). Linkages indicate some of the current challenges presented throughout this thesis. Source: created for this research.

[110] Note only some linkages are illustrated in Figure 6-4, however many more indirect and direct linkages are possible.

These 11 sustainability criteria for phosphorus security are explained and expanded in table 6-2.

***Table 6-2**. 11 Sustainability criteria for future phosphorus security. These criteria also address the current environmental, economic, institutional and ethical challenges relating to global phosphorus scarcity.*

Criterion	Description
1. Minimal waste	*Phosphorus security ensures that minimal phosphorus (and other resources) are wasted throughout the entire food production and consumption system.* Currently, there is a substantial amount of waste throughout the food production and consumption system (a large part which could be avoided and the remaining waste considered for recovery and reuse). Eighty percent of the phosphorus in rock mined for food production never reaches the food in our mouths. This waste occurs: during the production from phosphate rock (e.g. 5 tonnes of radioactive phosphogypsum by-product is generated for every 1 tonne of phosphate for fertilizer); during application of fertilizers (only about 10–25% of phosphorus in fertilizers is actually taken up by the crops); and during food production, distribution and consumption (approximately 50% is lost, e.g. in supermarket and household bins).
2. Healthy environment	*Phosphorus security ensures no net negative impact on the environment, including water, land and biota, including both at-source and downstream effects.* Currently, phosphorus losses from agricultural soils and sewage effluent are responsible for contributing to eutrophication of waterways leading to algal blooms across the globe, from the Baltic Sea, to the dead zones of Chesapeake Bay, to Australia's Great Barrier Reef. Growing phosphogysum piles risk contaminating groundwater and nearby land with radionuclides of uranium and thorium. Cadmium from phosphate rock is contaminating soils where no national regulation prevents toxic levels of the heavy metal from being applied to soils. These impacts are increasing. Future phosphorus use will need to be decoupled from such environmental degradation.
3. Minimal energy consumption	*Phosphorus security ensures phosphorus fertilizers are produced, transported used, recovered and managed in way that minimizes life cycle energy consumption.* The challenges arising from energy scarcity and climate change mean societies will need a substantial restructure to decouple their activities from energy consumption. Agriculture and food production account for a substantial share of the world's energy consumption, and greenhouse gas production. Extracting, processing and particularly transporting phosphate rock and associated commodities around the world is an energy intensive process. Indeed, phosphate rock is one of the most highly traded commodities in the world. Future systems will therefore need to source, use and re-use phosphorus in food production in a way that minimizes energy consumption.

4. Short & long term availability	*Phosphorus security ensures sufficient phosphorus of appropriate quality is physically available both in the short term and longer term for farmers to utilize in a timely way for fertilizers.* Phosphorus fertilizers need to be available to farmers at the appropriate time of the growing season to ensure optimum crop growth. Fertilizers are generally purchased annually and not stored for long periods. Short-term price spikes due to demand exceeding supply (such as the unprecedented phosphate rock price spike of 2008) can have serious impacts on farmer livelihoods and crop production. For example, in India there were farmer riots over fertilizer rationing and even instances of deaths. Phosphorus therefore needs to be available in the short- and long-term for food production.
5. Cost-effective system	*Phosphorus security ensures that the whole-of-society costs of producing, trading, using and recovering phosphorus are minimized.* Current life-cycle costs of phosphorus production (both market costs and externalities) are increasing due to the increasing costs of raw materials (including fossil fuels) and the declining grade and quality of remaining phosphate rock reserves. Increases in capital inputs caused by these increased costs represent an *opportunity cost*, diverting capital from other productive sectors of the economy. Future phosphorus security should seek to minimize both internal and external costs (to the whole-of-society) throughout the production and consumption system.
6. Fertile soil	*Phosphorus security ensures all the world's agricultural soils are sufficiently fertile to ensure high crop yields (with appropriate management).* Phosphorus is an essential nutrient for all living organisms. Without fertile soils in which to grow crops, the world cannot produce sufficient food. Phosphorus deficiency in plants results in poor crop and fruit growth. Currently, while soils in Europe and North America have surpassed critical soil phosphorus levels and pollution is the bigger problem, soils in sub-Saharan Africa are naturally very phosphorus-deficient and the problem is made worse because soil nutrients are often not replaced with what is lost through harvested crops. Therefore optimal phosphorus fertilizer applications should seek no under-, over- or imbalanced fertilizing.
7. Global food security	*Phosphorus security ensures sufficient fertilizers for food availability towards the goal of global food security.* Feeding humanity is likely to be one of this century's greatest challenges: in 2009 an unprecedented one-sixth of the world went hungry. Kofi Annan's African Green Revolution Alliance calls for increased fertilizer use in areas with low soil fertility and high food insecurity, recognising that fertilizers are essential to achieving the high crop yields that will be necessary to feed a growing world population and securing farmer livelihoods. However, where those fertilizers will come from has not been part of the discussion. Energy and water are understood to be limiting factors in achieving global food security, and phosphorus needs also to be considered and integrated.

8. Balanced diet	*Phosphorus security ensures all people have sufficient phosphorus intake for a healthy and balanced diet.* Phosphorus is an essential macronutrient for humans (and all living organisms). Phosphorus is an essential component of DNA, RNA and ATP (facilitating the transport of energy through the body). Although currently rare, phosphorus deficiency in humans can result in symptoms similar to Vitamin D deficiency (e.g. anemia, muscle weakness, bone pain, rickets, increased susceptibility to infection, and confusion). Therefore phosphorus nutrition for healthy bodies is important.
9. Minimal geopolitics	*Phosphorus security ensures geopolitical interests do not affect, and are not affected by, the sourcing, use or reuse of phosphorus for food production.* Today, while all farmers need access to phosphorus, five countries control approximately 90% of the world's remaining phosphate rock reserves. China, US and Morocco are the most important players. While the US is depleting its reserves and increasingly importing via Moroccan authorities, China demonstrated its role as a powerful player when it imposed a 135% export tariff in 2008 to secure its own domestic fertilizer needs, thereby effectively halting exports. Morocco currently occupies Western Sahara and controls its reserves, in defiance of UN resolutions.
10. Equitable allocation	*Phosphorus security ensures 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.* Today, poor farmers do not have equitable access to phosphorus fertilizers and the people of Western Sahara do not have equitable access to phosphate rock on their land. Because high-grade phosphate rock reserves are finite and will eventually be depleted, it is also the ethical responsibility of current generations to ensure future generations have access to phosphorus for food production (either through extending the life of current reserves, or by setting up new systems for recovery and re-use of phosphorus from other sources). Phosphorus security therefore ensures intra- and intergenerational equity with respect to access to phosphorus resources.
11. Effective governance	*Phosphorus security ensures independent, equitable and transparent governance of phosphorus resources for long-term food security.* Currently there are no explicit governance structures for the long-term sustainable management of phosphorus at the global scale. There is a lack of stakeholder consensus on the issues. This global non-governance is compounded by a lack of adequate policies or research. Further, there are no 'guardians' monitoring and ensuring adequate feedback and control of the system. Effective governance is therefore required to ensure that criteria 1–10 are satisfied.

While this chapter has synthesized the main arguments of this thesis, and provided conceptual framework based on 'phosphorus security' for possible solutions, chapter 8 will distil these into more concrete 'real world' conclusions and recommendations. Before such conclusions and recommendations are made, the role of transdisciplinarity in science is revisited and an argument for science as intervention (or creating change) is made.

CHAPTER 7: CREATING CHANGE TOWARDS SUSTAINABLE FUTURES

Chapter 3 articulated the transdisciplinary and systems approach to this research, including the application and adaptation (or fusion) of methods from the physical and social sciences. This chapter 7 explicitly argues for and reflects upon the 'change creation' elements of the transdisciplinary doctoral research consistent with critical systems thinking and soft systems methodology that seek sustainable improvements. Firstly, the distinction between the roles of science as 'observation' and 'intervention' are made (including the value of contributing to multiple outcome spaces – peer-review knowledge, the situation and mutual learning as explained in section 7.2). Secondly, a detailed and reflective account of the action research (and participant-observation) nature of this research is provided, including contributions to the multiple outcome spaces.

7.1 Science as intervention

The goal of this doctoral research, as stated in chapter 2, was to study both 'what is' (that is, science as *observation*), by conceptualizing phosphorus scarcity, and, equally 'what could be' or more precisely, 'what would a preferred future look like'? (that is, science as *intervention*), by developing scenarios and criteria for phosphorus security at the global scale and the national stakeholder workshop.

'Science as observation' is the basis of traditional forms of scientific research (argued most notably by Popper, as critiqued by Midgley (2003). Popper argues that such observation must be subject to a structured method that facilitates supposedly 'independent' observations, and must be scrutinized by the academic community in order to be considered scientific. Contributing to peer-reviewed academic knowledge through rigorous and scholarly research is the traditional outcome of doctoral research. The "scholarship of discovery" (Boyer, 1990) is important because it can supposedly add new independent insights to theory and/or content once it has undergone a structured peer review process.

However as early as 1947 Lewin proposed that "*science should be harnessed for the benefit of human society*" (Midgley, 2003, p.81) and hence a new approach of action research was born (Lewin, 1946, 1947). Lewin believes that action research inherently requires intervention, that perceived societal problems should be addressed through scientific inquiry with the intention to improve the situation. In her critique of the intervention versus observation divide, Wadsworth (2007) reflects on a period of change almost four decades ago:

> *Certainly a whole generation felt we had to go elsewhere in the 1970s for ideas to work with the numerous 'problems without names' and how to research how to make change, not just (even critically) observe things as they were. Many of us turned to feminism, the counterculture, third force psychology, critical theory, phenomenology, new left Marxism, interpretivism, constructivism and participatory action research.* (p.158)

Midgely (2003) defines intervention as "*purposeful action by an agent to create change*" (p. 79), and indeed renegotiates the observation versus intervention divide by contending that observation is in itself a form of intervention because "*observers are part of the reality they observe: they cannot observe* *from outside the systems of mutual causality in which they participate*"[111] (p.84). For example, observing social structures through in-depth stakeholder interviews (such as those undertaken in this doctoral research) invariably impacts on the respondents or intervenes in the context under study to a greater or lesser extent. Midgley even sees publishing as a form of intervention:

> *If science is not concerned with action, why bother with the act of publishing? Even scientists in the "purest" disciplines wish to intervene in scientific discourse (which, of course, interfaces with wider social discourses)* (Midgley, 2001, p.625).

In 1990, Boyer called for three new forms of scholarship in addition to the scholarship of *discovery*. He proposed: 1. The scholarship of *integration*; 2. the scholarship of *application*; and 3. the scholarship of *teaching*. This thesis aspires to this expanded understanding of scholarship. 'The scholarship of integration' is particularly relevant to the intentions of this doctoral study and is elaborated by Schön as: "*putting [isolated facts] into perspective...making connections across disciplines, placing the specialties in larger context, illuminating data in a revealing way, often educating non-specialists, too*" (Schön, 1995). In line with the intentions of transdisciplinary research as being application-oriented and socially distributed (Gibbons et al., 1994), Lawrence and Despres remind us that "*universities are the locus not only of knowledge production but also of knowledge transmission*" (Lawrence and Despres, 2004, p.398). As will be explained in detail below, this thesis has also aimed to communicate the new knowledge to target audiences.

Figure 7-1 revisits some of the theoretical and methodological approaches introduced in chapter 6, and juxtaposes them on a different spectrum: the role/intentions of science from intervention to observation (on the y-axis), and indicates their relative embrace of multiple methodologies or epistemologies (on a spectrum from disciplinary research to 'meta'-disciplinary research approaches on the x-axis).

[111] Based on systems thinking and complexity logic.

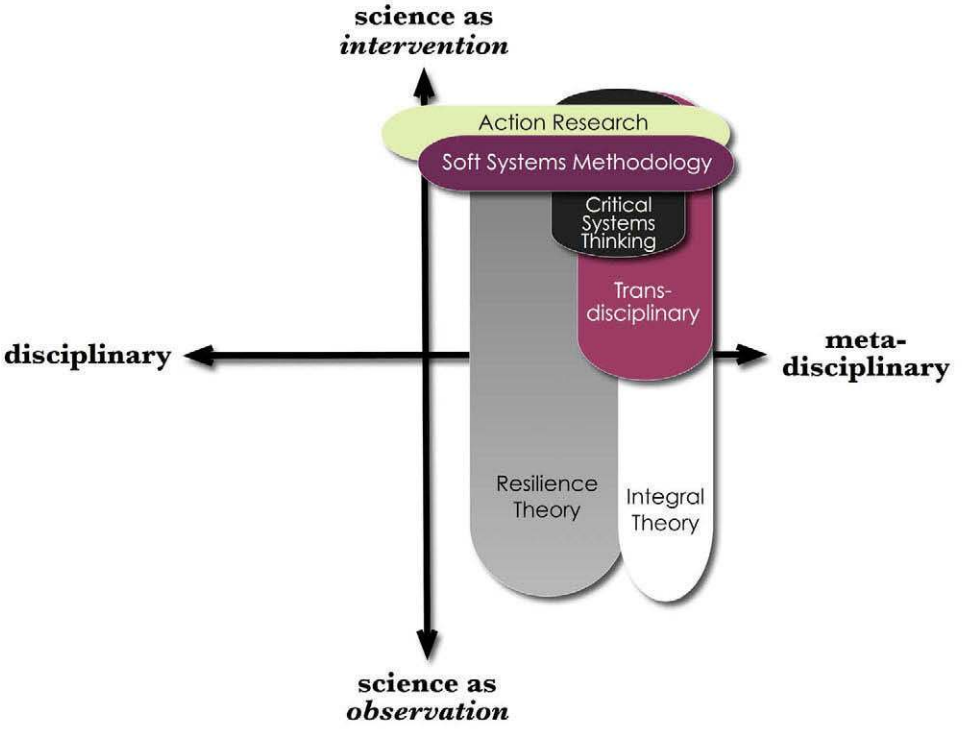

***Figure 7-1**: Some research theories and approaches that explicitly aim (at least in part) to create change towards more sustainable (or desirable) futures (i.e. concentrated at the top end of the y-axis spectrum of science as intervention versus science as observation). Many of these approaches also involve multiple methodologies or even epistemologies that transgress disciplinary boundaries (i.e. they are concentrated on the right end of the x-axis spectrum disciplinary to 'meta'-disciplinary research). Source: created for this research.*

In the abstract of their book *Global Environmental Assessments: Information and Influence*, Mitchell et al. (2006) further support this notion of societal engagement:

> *global environmental assessments are more likely to be influential if the process is perceived not only as scientifically credible but also as salient to policy concerns and as generated through legitimate means*.

The authors further suggest that while substance is critical,

> *influence is often determined more by the process that generated it and by external factors affecting the receptiveness of different audiences. Assessments that involve ongoing interactions among scientists, stakeholders, and policymakers prove particularly likely to influence behaviors* (Mitchell et al., 2006).

An institutional example of 'science as intervention' is the structure of the Institute for Sustainable Futures (ISF)[112] at the University of Technology, Sydney, where this doctoral research was in part undertaken. The mission of ISF is '*to create change towards sustainable futures*' through research. Both post-graduate and consultancy research is often undertaken by explicit

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[112] See ISF's website for a description of its research approach: www.isf.uts.edu.au.

intervention in the situation under investigation (such as engaging government, industry, community and other research stakeholders) in the research inquiry, change process and knowledge production. This process recognizes that research, mutual learning and co-generation of knowledge by researchers and stakeholders is often a powerful tool for creating change and making academic research more socially robust.

7.2 Three outcome spaces: peer-reviewed knowledge, societal context and mutual learning

As discussed in section 3.1, transdisciplinary research often explicitly aims to contribute in multiple ways beyond peer-reviewed knowledge. This sustainable futures research aims to contribute to both academic knowledge *and* societal knowledge and practices. That is, it aims to contribute/communicate to the multiple users of the knowledge, including researchers/scientists, industry and policy-makers. Considerable progress has been made by researchers in articulating how transdisciplinary academic research can contribute to what has been termed multiple 'outcomes spaces' (Mitchell and Willetts, 2009). In their explanation of this notion, Mitchell and Willetts identify three key outcome spaces (figure 7-2).

Figure 7-2: *Three outcome spaces of transdisciplinary research: 1. peer-reviewed academic knowledge, 2. the problem situation or context, and 3. Transformative or mutual learning. Adapted from Mitchell and Willetts (2009) and Carew and Wickson (2006).*

Mitchell and Willetts explain that the situation outcome space is "*the situation or problem space which may be a sector, a situation, a societal issue or problem or an aspect of practice in some domain*" (2009, p.6), while the mutual learning outcome space relates to "*transformational change within the researcher, and mutual (perhaps transformational) learning by stakeholders involved in, or influenced by the research*". Transformational and/or mutual learning can occur individually through critical reflection and through deliberation in groups.

Contributing to peer-reviewed academic knowledge through rigorous and scholarly research ("The scholarship of discovery" (Boyer, 1990)) is the traditional outcome space of doctoral research (as described earlier). Benefits of engaging in and contributing to the situation's outcome space and mutual learning are less well defined and acknowledged, though they can be equally important.

The discussion below combines personal critical reflections from the process of undertaking this doctoral study, with the collective insights developed from the 'community of practice' approach to doctoral research adopted at ISF[113]. Examples of how I have engaged in these outcome spaces are provided in section 7.2.3 and subsequent sections.

7.2.1 Benefits of contributing to situation (societal) outcome spaces

Whilst contributing to academic knowledge is important, it can often be of limited societal benefit or effect outside academia even though it may be addressing a societal area of interest. Accessing journal articles often requires subscriptions or payment and their language may be inaccessible to some readers. Furthermore, stakeholders engaged in policy at the frontline may not have time to search a Science Direct database to keep up to date with the growing body of research. In some instances, the target audience of the research may not be interested in the doctoral researchers' findings because they may perceive it to have negative implications for their work, or they may not have time to engage with the academic jargon to reach the underlying message relevant to their role, or they may not have time or interest to deal with 'yet another important issue'.

Engaging in the 'situation' outcome space therefore allows:

- **Communicating to targeted audiences**. For example, the 'real-world' users of the knowledge (such as farmers, policy-makers and the fertilizer industry in the case of this doctoral research). This may require the use of appropriate language and framing of the issue to the target group, an appropriate medium and an appropriate process for engagement or communication. For example, the research findings here were summarized and converted into a series of 'two pager' information sheets that could be physically handed out (or emailed) to target audiences[114]. Further, research findings were made available (in more widely accessible language) via a phosphorus research website (discussed further below).
- **Timely communication and change creation**. Journal articles and theses can take years to be published, while the 'real-world' context changes rapidly (as was the case in this doctoral study, as described in section 7.3). as a result, opportunities to communicate research findings may be missed. Presenting at conferences is an excellent interim measure, however this tends to only reach a limited (often academic) audience, and not necessarily the target of the research findings. For this reason, research findings were also communicated more promptly through the website, and via the media (again, as described below).
- **Increasing socially robust research through stakeholder review**. In the same way that contributing and engaging in academic knowledge production involves a *peer*-review process to critique and ground-truth the researchers' work, engaging in the societal context can also facilitate a form of *stakeholder*-review process that also reality-checks and critiques the arguments, assumptions and language of the research. In this case, a substantial amount of critique was received, either directly or indirectly from other scientists, the fertilizer industry, farmers and natural resource managers. An example of a public scientific critique of this doctoral research can be seen in Ward

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[113] For example, the post-doctoral program at ISF, facilitated by Professor Mitchell, involves annual research retreats, fortnightly Groups for Accountability and Support (GAS) meetings, and fortnightly postgraduate 'roundtables' involving explicit critical reflection on a broad range of topics related to transdisciplinary sustainability research theory and practice (see Willetts and Mitchell (2006) for an elaboration on the 'community of practice' approach at ISF).

[114] These can be downloaded from http://phosphorusfutures.net/files/1_P_DCordell.pdf and http://phosphorusfutures.net/files/2_Peak%20P_SWhite_DCordell.pdf .

(2008), an article that that seeks to critique the peak phosphorus analysis presented in this thesis. These forms of critique enabled critical reflection and improvement of either the research analysis or how the research was communicated or framed.

- **New insights**: Thinking through how to communicate one's research to different stakeholders, including the community, can often yield new insights relevant to the research. This process, for example, forces the researcher to focus and reflect on what is the key message of this research? What exactly am I trying to say? And to whom? An example here was the preparation for a high-level public lecture held at the University of Technology, Sydney (Cordell, 2009b), which ultimately led to improved framing of the 'phosphorus security' goal developed in this thesis. Part of the communication strategy developed in this doctoral study is provided in Appendix F-4.
- **Moral contribution**: Do researchers (particularly sustainability researchers) have a moral obligation to 'give back' to the situation/context beyond providing academic knowledge? That is, do they have an obligation to ensure research results in societal benefit? This is certainly supported explicitly by action research (Lewin, 1947; Midgley, 2003) and other forms of research, such as participatory social research which often requires the researcher to give back to the participants or participants' community. Indeed, this issue was the theme of an international workshop held at Linköping University entitled: "*Linking science to societal benefit*" (Linköping University, 2009).

7.2.2 Benefits of transformative or mutual learning

Some benefits of contributing to the transformative or mutual learning outcome space include:

- Facilitating transformational *eureka* moments in the targeted stakeholder and/or researcher; often creating a substantial shift in thinking about the problem situation;
- Facilitating ownership of the ideas by stakeholders who are in a position to implement change (often stakeholders don't like to be told what to do or what they are doing wrong, but if they are part of the journey of discovery, then tend to 'own' the solution and are therefore more likely to implement it); and
- Mutual learning is in some respects analogous to the concept of 'emergence' in systems thinking, the idea that the whole is greater than the sum of the parts. In the same way, research or learning undertaken collaboratively (co-learning), rather than a doctoral student researching more or less in isolation, can generate new insights and result in ongoing networks.

This focus on the process and on co-learning between researchers and stakeholders is supported by Clark et al. (2006) who, following an analysis of the influence of Global Environmental Assessments (GEA), propose "*to be influential, potential users must view a GEA as salient and legitimate as well as credible"* (p.15). The scientists draw five key recommendations:

- Focus on the process, not the report;
- Focus on salience and legitimacy as well as credibility;
- Assess with multiple audiences in mind;
- Involve stakeholders and connect with existing networks; and
- Develop influence over time (Clark et al., (2006)).

7.2.3 Contributions of this thesis to three outcome spaces

The primary contributions of this doctoral research to the three transdisciplinary outcome spaces, particularly peer-reviewed knowledge and the situation are summarized in table 7-1. Secondary contributions (such as citations of these contributions or the impact of these contributions) are discussed in sections 7.3 and 7.4 below.

***Table 7-1**: Key contributions to the three outcome spaces: Peer reviewed academic knowledge, situation and mutual learning (expanded in Appendix F-2, F-3).*

Peer-reviewed knowledge	Situation/context	Mutual learning

• five international peer-reviewed articles (Cordell, 2008b; Cordell et al., 2009a; Cordell et al., 2009b; Cordell, submitted; Cordell and White, submitted);
• this doctoral thesis;
• five conference presentations (including papers, posters or powerpoints):
  o WWW*(Cordell, 2007a)
  o GECAFS*(Cordell, 2007b)
  o ANZSYS* (Cordell, 2008b)
  o Avlopps*(Cordell, 2009c)
  o Nutrient Recovery*(Cordell et al., 2009b)
• two intensive (1–2 week) workshop/courses (two full-length papers and presentations):
  o THEMES^(Kerschner and Cordell, 2007)
  o SENSE^ (Cordell, 2008c)
  o ACSPRI^
• two short (1–2 day) workshops (two presentations):
  o World Resources Forum^ (Cordell, 2009b; Stamp et al., 2009a)
  o E-CReW^ Resource Economics(Cordell, 2007c).
	• co-founding the Global Phosphorus Research Initiative (GPRI);
	• co-developing the GPRI website www.phosphorusfutures.net;
	• Australian national stakeholder workshop (Cordell and White, 2008, 2009);
	• research reports (Cordell and White, 2008, 2009);
	• information sheets (Cordell, 2008a; White and Cordell, 2008);
	• professional publications (see list in Appendix F-3);
	• UTSpeaks public lecture aired on national TV(ABC Fora, 2009);
	• media (see list in Appendix F-3);
	• invitations to present at Australian and international academic, industry and community conferences (e.g. the Australian Fertilizer outlook) (White and Cordell, 2009).
		• via in-depth stakeholder interviews;
		• via Australian national workshop;
		• via networking, meetings, communications (in some instances, stakeholders have provided direct or indirect evidence of mutual learning).

** WWW = World Water Week, Stockholm; GECAFS = Global Environmental Change and Food Systems conference; ANZSYS = Australia and New Zealand Systems conference; Avlopps = (translation) the Sanitation and Recovery/Nutrient cycles conference; Nutrient Recovery = the International Conference on Nutrient Recovery from Wastewater Streams, Vancouver 2009*
^ THEMES = Institutional Analysis of Sustainability Problems Marie Curie Summer School; SENSE = Earth System Governance summer school; ACSPRI = Australian Consortium for Social and Political Research Incorporated; World Resources Forum = PhD Workshop on governance of scarce elements held at the 2009 World Resources Forum; E-CReW = Early Career Resource Economics Workshop;

7.3 A participant observer in a rapidly changing field

The field under investigation in this doctoral research has undergone rapid changes since the commencement of the research in April 2006, most notably resulting in the emergence of a global phosphorus scarcity (and indeed 'peak phosphorus') discourse related to food security that was previously almost non-existent (as described in chapter 5.6). In line with a transdisciplinary (and indeed 'resilient') research approach requiring a flexible and adaptive methodology (described in further detail below), I continued observing and reporting on the significant changes and events. As indicated earlier and supported by Midgely's critique of independent observation as an 'impossibility', I have simultaneously been a participant, influencing the context. In Gold's categorisation this would be classed as 'observer-as-participant' (Gold, 1958, p. 221). Participant observation is a research methodology that developed in sociology and social anthropology to facilitate improved understanding of the practices and beliefs of a specific social group under study. Gold further articulates this as a spectrum from 'complete observer' through to 'complete participant' depending on the nature and level of involvement (Gold, 1958). Figure 7-3 captures some of the key observed developments in the field of study and also indicates how I engaged and participated in the context (this timeline is explained in text in Appendix F-1 and F-2).

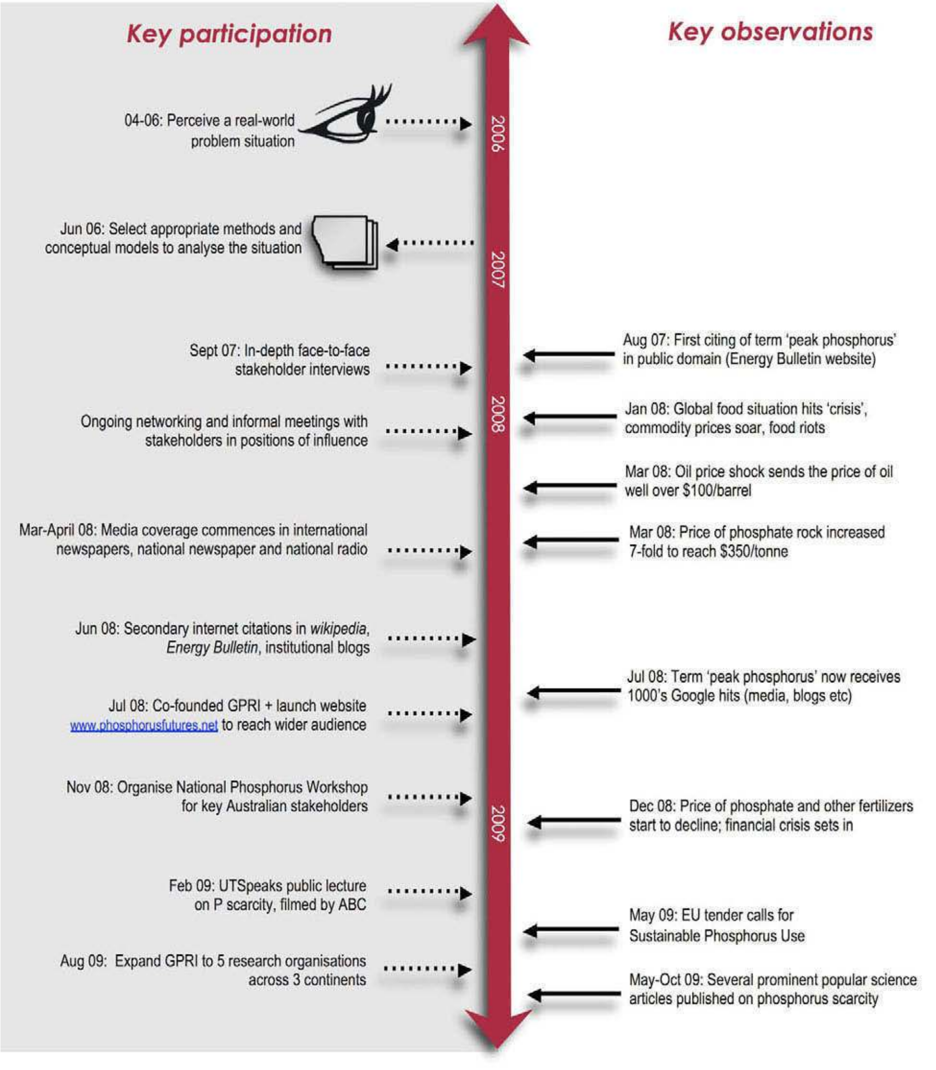

Figure 7-3: *Key observations and participation relating to global phosphorus scarcity over the period 2006-2009. See Appendix F-1 and F-2. Source: created for this research.*

As described earlier, the basis of action research is systematic intervention in a situation in order to improve it. Lewin describes the approach as "*a spiral of steps, each of which is composed of a circle of planning, action, and fact-finding about the result of the action*" (Lewin, 1946). With guidance from the principles underlying action research, and from transdisciplinary, soft systems methodology and resilience theory, a structured yet flexible methodological approach was taken to engage in the context, to create change at the right time, in the right way and to the right audience. Such an approach needed to be systematic and critically reflective yet intentionally flexible, to respond to new knowledge in a timely and appropriate way as it emerged through engagement. Figure 7-4 conceptualizes the process as dynamic engagement in the situation, the theory and with the stakeholders. The nature of the engagement with these spaces was both 'designed' (such as the stakeholder interviews) and responsive and flexible to the changes in the field (such as the high-profile public lecture).

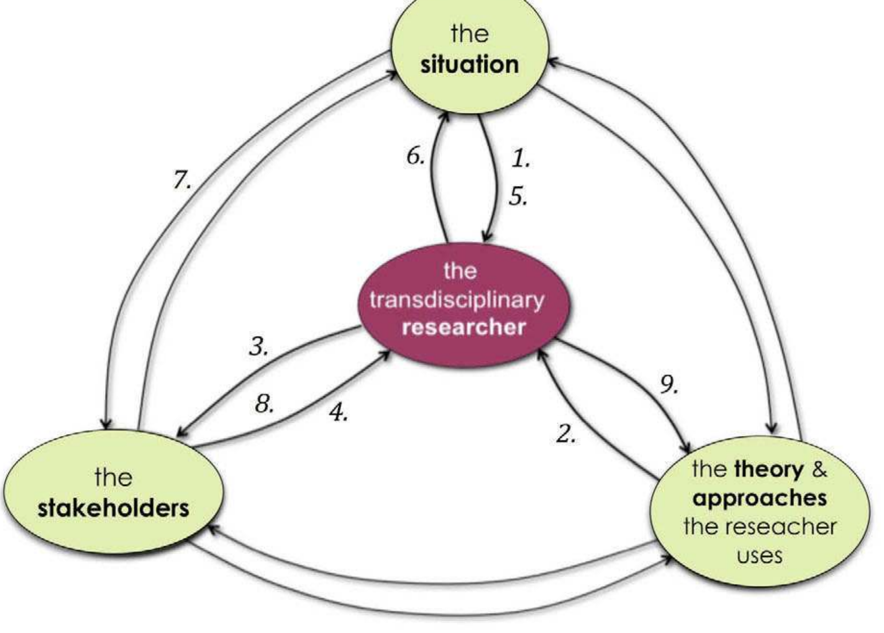

***Figure 7-4**: The dynamic journey of a transdisciplinary, systems-thinking, action-researching doctoral researcher. Modified from Armson (2008) 'the systems practitioner'.*

The following chronological events exemplify the process[115] (with attention to figure 7-4):

1. I perceived a problem situation and commenced a PhD in 2006 to investigate it.
2. As with any researcher/observer, I was influenced by past and present academic experiences (for example I had worked at a transdisciplinary research institute in the fields of sustainable water, sanitation and resource management since 2000).
3. The formal stakeholder interviews were undertaken as scheduled.
4. These in-depth interviews resulted in mutual learning and yielded data to analyze.
5. Independent of this research, the price of phosphate rock rose rapidly by 800% (at the same time other external influences such as the global food crisis put food security and policy back on the political agenda). I observed and monitored these events at a macro scale.
6. Due to these rapid changes and a crucial need to engage and communicate in a timely way, additional research communication strategies were devised to supplement the

[115] These are not intended to capture every event/action; rather they provide sufficient and diverse examples.

slower journal review/publication process (for example, the first journal article, *Paper I*, took over 900 days to be published from first submitting it). Therefore:

- I co-founded the Global Phosphorus Research Initiative (GPRI)[116] with colleagues at both host universities. The Initiative aims to "*to facilitate quality interdisciplinary research on global phosphorus security for future food production. In addition to research, the GPRI also facilitates networking, dialogue and awareness raising among stakeholders and the community on global phosphorus scarcity and possible solutions*" (figure 7-5);
- I co-developed the GPRI website: www.phosphorusfutures.net to contribute to new public knowledge in a timely and widely accessible way (see Appendix F-5); and
- I publicized the issues in international and national print and radio media (for example, *Nature*, Australia's *ABC Radio National*, London's *The Times*, Canada's *The Globe and Mail*, France's *Le Monde*) see Appendix F-3).

Figure 7-5: *logo of the Global Phosphorus Research Initiative (GPRI). The GPRI was developed as a timely outcome during this doctoral research. The aim of the GPRI is "to facilitate quality interdisciplinary research on global phosphorus security for future food security". Source: logo created for this research, see: www.phosphorusfutures.net*

7. As a result of the external factors (described in point 5 above) and the responsive strategy described in point 6 above, the ongoing knowledge generated in this research was subsequently used/quoted internationally by governments, EU and UN bodies, industry and other research/special interest institutions, including for example, official European Commission reports (European Commission, 2009a), an Expert Report to the FAO World Summit on Food Security (Fischer et al., 2009), the Dutch multi-

[116] The GPRI has since expanded to include five research organisations across three continents (including: 1. the Institute for Sustainable Futures at the University of Technology, Sydney (UTS), 2. the Department of Water and Environmental Studies at Linköping University, Sweden; 3. The Stockholm Environment Institute (SEI) in Sweden, 4. The University of British Columbia (UBC) in Canada and 5. Wageningen University in The Netherlands).

stakeholder partnership Nutrient Flow Task Group policy paper (Smit et al., 2009), The Broker (Rosemarin et al., 2009), the *Australian Farm Journal* (Cartledge, 2009), the NSW State Government (NSW Department of Primary Industries, 2008), the Scottish Ministry (Scottish Ministry, 2008), The European Phosphate Industry (CEEP, 2009) and Australia's Consumer Association's magazine (CHOICE Magazine, 2009). This in turn resulted in more media and stakeholder interest (see Appendix F-2 and F-3).

8. The growing concern and exposure of the issue (attributable particularly to the phosphate price spike), provided a window of opportunity to engage key Australian stakeholders in the national case study undertaken as part of this research. I organized a national phosphorus workshop to bring together key Australian stakeholders to discuss and deliberate over the implications of global phosphate scarcity (and related sustainability and ethical issues) for Australia's food production and consumption system and vision possible future scenarios (using backcasting, see Appendix E)[117]. In addition to the workshop content contributing to the research analysis as primary data (published in Paper V and Cordell and White, 2008), the workshop also resulted in mutual learning and a commitment to further the multi-stakeholder research and policy dialogue regarding the implications for global phosphorus scarcity for Australia.
9. The engagement in the situation resulted in improved understanding and analysis of the problem situation regarding phosphorus scarcity (contributing to peer-reviewed knowledge). It is also hoped that this will contribute to transdisciplinary and systemic research approaches for creating change towards sustainable futures – for example, contributions to Mitchell (2009) through participatory workshops.

7.4 Measuring scientific intervention

Measuring the of the change-creation impact of one's research can be difficult because:

- Appropriate indicators of change are hard to find, for example changes may not be visible in the public domain if they are occurring inside an individual's head (or behind closed doors) and may require time and resource-intensive intentional evaluation such as follow-up interviews;
- Change is often the result of multiple interacting events so it is hard to distil how much is due to a specific action; and
- Change can be a slow process, and may therefore not be measurable during the timeframes of evaluation.

However, one relatively simple indicator of impact in at least peer-reviewed knowledge and the situation outcome spaces is the number of citations in scholarly documents, governmental and industry documents, media and other popular scientific media. Scholarly citations are problematic to measure at this stage, due to the significant lag time of journal papers. However, citations of the key contributions summarized in F-3 have been observed in a number of international academic peer-reviewed papers, EU and FAO reports, conference presentations and online material. Due to the opportune timing of events (shown in the timeline in figure 7-3), the research findings have also been cited extensively in a range of international print media and on radio and television (listed in Appendix F-3). Citations have

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[117]See: http://phosphorusfutures.net/index.php?option=com_content&task=view&id=23&Itemid=36#Future_of_Phosphorus_workshop

also been observed in governmental reports and websites (see Appendix F-3). Other online input is evidenced a) by the growing number of Google hits of key terms (for example, "peak phosphorus" surged from zero hits in early 2007 to over 2 million in mid-2009), and b) directly through feedback in personal emails from researchers, citizens, industry representatives and public servants.

This chapter has followed from chapter 3 and argued why, and documented how, this transdisciplinary thesis legitimately sits at the 'intervention' or change creation end of the spectrum of science as observation versus intervention. Final conclusions and recommendations in the following chapter 8 are made in this light.

CHAPTER 8: RECOMMENDATIONS AND CONCLUDING REMARKS

Chapter 7 presented the argument for 'science as intervention' and why seeking sustainable improvements was part of the aim of this thesis. This chapter 8 closes the central argument of this thesis with concluding remarks and concrete 'real world' recommendations for sustainable improvements.

8.1 Concluding remarks

The story of phosphorus began with the search for the philosopher's stone, and centuries later highlighted the critical role of phosphorus in soil fertility and crop growth, and eventually implicated the nutrient in the global environmental challenge of eutrophication. Yet we are on the brink of yet another emerging chapter: global phosphorus scarcity. This thesis has articulated, analyzed and synthesized the physical and institutional dimensions of global phosphorus scarcity in the specific context of food security and sustainable development. The thesis proposes a new global goal – phosphorus security – to be integrated into the dominant discourses and policy debates on global food security and global environmental change.

Five key conclusions are drawn from this research, which are in turn linked to five research recommendations. Consistent with the nature of transdisciplinary research as being integrated (and indeed the overarching aim that this doctoral research be undertaken *in a holistic way*), in most cases each conclusion-recommendation pair respond to multiple research questions and specific objectives. These are indicated below.

1. Global phosphorus scarcity is a serious threat to future food security

The first research question of this thesis asked specifically, *in what ways might the current approach to sourcing and using phosphorus depart from sustainability principles in the context of global food security?*. Addressing this question was facilitated in part by the first specific objective, *to quantitatively and qualitatively analyze and conceptualize the sustainability implications of the phosphorus situation for current and future food security*. The current usage patterns of phosphorus are unsustainable and threaten the ability of humanity to produce food in the future. The use of systems theories and methodologies (such as substance flows analysis and soft systems methodology) facilitated the overall finding that the unsustainable situation pervades the entire food production and consumption system (that is, the problem is not simply regarding scarcity of phosphate rock, but extends from mine to field to fork). Further, the combination of qualitative and quantitative analyses contributed to finding a much broader and integrated conceptualization of phosphorus scarcity – which has been defined here by at least five dimensions, including:

1. *Physical* phosphorus scarcity – the quantitative peak phosphorus analysis found that while phosphorus has no substitute in food production, the main source used in modern agriculture, high grade phosphate rock, is non-renewable and peak phosphorus is estimated to occur by 2035 while demand is expected to increase;
2. *Managerial* phosphorus scarcity – the quantitative phosphorus flows analysis found that in both the global and national (Australian) food production and consumption system, there are substantial inefficiencies and losses throughout the system, some of which are avoidable, others which are unavoidable;

3. *Economic* phosphorus scarcity – the qualitative soft systems analysis found that while all the world's farmers need access to sufficient fertilizers, only those with purchasing power can access fertilizer markets;
4. *Institutional* phosphorus scarcity – the qualitative institutional, soft systems and stakeholder analyses found there is a lack of institutional structures at the international level that explicitly aim to ensure long-term availability of, and accessibility to, global phosphorus resources for food production, leading to a lack of effective governance (as described in detail in conclusion 4 below); and
5. *Geopolitical* phosphorus scarcity – the qualitative institutional, soft systems and stakeholder analyses found that most of the world's remaining phosphate reserves are subject to substantial geopolitical tensions, and that 90% of the world's remaining high-grade phosphate rock reserves are controlled by just five countries.

To determine in what ways the system *departed from sustainability principles* in the context of *future* food security, the soft systems analysis defined a future ideal sustainable system, which could be compared to the business-as-usual situation in the future scenarios analysis. In terms of meeting future food demand, the phosphorus supply-demand scenarios indicate a substantial gap between future demand and supply in the probable (business-as-usual) scenario. This could lead to a 'hard-landing' situation of further fertilizer price spikes, increased waste and pollution (including eutrophication), increased energy consumption associated with the production and trade of phosphorus fertilizers, reduced farmer access to phosphorus, reduced global crop yields and increased food insecurity. Responding specifically to the 3rd Research Question (*what improvements would be required, in relation to the current phosphorus situation to move towards global food security?*) the preferred (sustainable) scenario indicates that a dramatic reduction in demand and high recovery rate of all sources of phosphorus will be required in the long term. Achieving a preferred 'soft landing' situation will likely require substantial technical, institutional and social changes to improve the phosphorus scarcity situation and ensure future phosphorus security.

The second specific objective, *to develop a goal and associated criteria for sustainable governance and management of global phosphorus resources for food security*, also guided the analysis for answering the 3rd research question. The goal of 'phosphorus security' was proposed in response to the five dimensions of global phosphorus scarcity (and the future scenarios analysis) and has been defined as compliance with a set of 11 sustainability criteria that address social dimensions (such as farmer livelihoods), ecological dimensions (such as soil fertility), economic dimensions (such as cost-effectiveness) and environmental dimensions (such as minimising waste). The criteria (described in more detail in table 6-2, chapter 6.3) include:

Criteria for global phosphorus security:

1. Minimal waste
2. Healthy environment
3. Minimal energy consumption
4. Short- and long-term availability
5. Cost-effective system
6. Fertile soil
7. Global food security
8. Balanced diet
9. Minimal geopolitics
10. Equitable allocation
11. Effective governance

2. Phosphorus data is scarce

Undertaking both the quantitative (e.g. peak phosphorus and substance flows analysis) and qualitative analyses (e.g. the institutional analysis) following the specific objectives a) and c), inadvertently revealed a concerning lack of available, reliable and consistent data on global phosphorus resources and consumption patterns in the global food system upon which a) researchers, scientists and observers can base analyses and b) phosphorus users, producers and policy-makers can make informed decisions. The information that is available is not independent, transparent or trustworthy, and it has not been produced and managed in a participatory manner. This has significant implications for the governance of phosphorus (in response to the second research question regarding *the adequacy of the global governance and management of phosphorus*), in terms of power, legitimacy and accountability. For example, because most primary phosphate rock data is produced and owned by individual companies and is often not publicly available, power imbalances occur between current data producers (such as the mining and fertilizer industry) and data users (such as farmers and policy-makers). As a result, farmers and policy-makers are unable to make informed judgements about the future availability and security of a resource critical for crop growth, livelihoods and national food security.

3. Phosphorus scarcity largely missing from key discourses

The critical review of three global sustainability discourses (chapter 4) contributed to addressing the 2nd Research Question (*What can an analysis of the 'human-activity' system reveal about the adequacy of the global governance and management of phosphorus, in relation to food security?*) by revealing that the global phosphorus scarcity discourse put forward in this thesis is currently missing to a large degree from most research and policy frameworks related to global food security, global environmental change and global resource scarcity. For example, while the International Geosphere-Biosphere Program identifies some of the most important *physical* challenges of global environmental change, and the Earth System Governance project identifies the *institutional* challenges, neither currently addresses the challenges arising from phosphorus scarcity. Similarly, while phosphorus is clearly critical for food availability, and has indeed contributed to feeding billions of people over the past century, there has been a significant lack of concern, research and discussion about the security of phosphorus supplies in the long-term future. Whilst the finite nature of phosphate rock has been acknowledged within some fields (such as sustainable sanitation and industrial ecology), these are the minority and in most cases not explicitly connected to the global food system. The main conceptualizations of phosphorus and the environment have also rarely been concerned with global phosphorus scarcity. Rather, they commonly relate to pollution.

However the situation changed rapidly in 2008 with the fertilizer price shock coupled with the global food crisis and energy crisis. This combination of events resulted in increased discussions on phosphorus scarcity linked to food production and some of this discussion has been informed by this doctoral research. While a more explicit discourse on global phosphorus scarcity appears to be emerging, the question still remains as to how long it will take for the discourse to influence institutions and hence, for phosphorus resources to be governed in a meaningful way that will contribute to long-term global food availability.

4. Lack of effective governance of phosphorus resources

With attention to the 2nd Research Question regarding *the adequacy of the global governance and management of phosphorus*, findings from three qualitative analyses of the *human-activity* system (soft systems analysis, stakeholder interviews and institutional analysis) together indicated a substantial lack of effective governance of phosphorus resources for food security.

Shortcomings of the current situation include:

- There appears to be little stakeholder agreement or consensus on the phosphorus situation among specific key stakeholders related to global phosphorus and food security and some perceptions are inconsistent or conflicting;
- The system boundary is currently narrowly defined; for example, some actors (human or non-human) are included, while others are excluded/marginalized (as depicted in figure 6-1). This has perpetuated power imbalances between actors. The mandate of the sector that currently dominates the management of global phosphorus resources – the fertilizer industry – is limited to a narrow focus on phosphate rock, and short-term time frames. This focus is also reflected for example in the implied system boundary adopted by the UN fertilizer demand expert.
- There is a 'lack of fit' between the physical global phosphorus-food system and the institutional arrangements around the system. Institutional structures are fragmented and this can lead to an ambiguity of roles and responsibilities. Phosphorus scarcity is currently not a priority within any sector and has no institutional home. For example, there is no guardian or overall coordination ensuring long-term phosphorus availability and accessibility for global food production. Finally, partly as a consequence of data scarcity, there is a lack of foresight regarding the long-term future and currently, no platform for dialogue and consensus building exists.
- In the absence of any explicit governance structure covering the whole phosphorus-food system, it is the market system which by default governs global phosphorus resources. The market operating alone is not sufficient to manage the wider system in a sustainable, equitable and timely manner.
- There are insufficient monitoring, feedback and control loops within the system to ensure that the core functions of the system (such as short- and long-term phosphorus availability) can be sustained. Market feedback loops (such as price signals) are by themselves not sufficient. For example, they cannot ensure long-term availability and equitable accessibility by all farmers.

5. Multi-scale and context- specific analyses

The second specific objective, *to analyze such implications for a significant national food production and consumption system* was met via a national case study (of Australia) that combined many of the same methods used for the global scale analysis (that is, a phosphorus flows analysis, soft system methodology) in addition to a stakeholder workshop. While the global scale analysis is clearly important (as noted in point 1 above), the national case study for Australia (and the minor regional example for Africa) indicate that the implications of scarcity at lower geographical/political scales can be very context specific. For example, the Australian case study indicates that although Australia doesn't have a current food security problem per se, Australian soils are naturally phosphorus deficient and as a net food-producing nation, Australia is highly dependent on both imported and domestic phosphorus resources. Yet only a very small fraction (less than 5%) of the phosphorus in fertilizers applied by Australian farmers ends up in the food Australian's eat, because most is embodied in agricultural exports shipped off Australian shores, or temporarily locked in soils or lost to waterways. The African analysis indicated the substantial phosphorus inequity: the continent produces around 30% of the world's phosphate rock, yet simultaneously has some of the lowest phosphorus fertilizer application rates in the world and has the highest level of food insecurity.

Responses to this global problem will also have to be implemented on multiple scales, including the national scale to respond in part to more context-specific situations. That is, while global phosphorus scarcity is a problem of global proportions and can affect the ability of any nation or region to ensure food security, responses will need to be context-specific. Such regional variations relate to economic, geological and social factors, such as dependence on fertilizers, soil fertility status, food security status, and whether the country or region is a net food producer or consumer.

8.2 Recommendations

This study has aimed to reconceptualize and analyze the nature of the phosphorus problem situation and seek sustainable improvements that are both research and policy relevant. With these aims in mind, specific recommendations for further research, and recommendations for policies which address the conclusions outlined above, are provided here. In some instances, research and policy recommendations are inseparable – for example, increased accountability in Research Recommendation 2 is directly linked to policy recommendation pertaining to improved governance.

Research recommendation 1: Improved scenarios for meeting future phosphorus demand

Because phosphorus scarcity is a global problem that directly affects future food production, it is important to further address the question of what would be required to meet future phosphorus demand to secure food availability. Responses to this problem could also be embedded in the broader goal of global phosphorus security, which ensures phosphorus use is decoupled from environmental degradation, social injustices and ensures farmer livelihoods as outlined in the criteria in the first conclusion and expanded in section 6.3. Such scenarios could further develop the initial scenarios analysis presented in *Paper IV*.

On the demand side, an important question is what are the most effective means to reduce the demand for phosphorus from the entire food production and consumption system, taking into account important sustainability criteria for phosphorus security? As conceptualized in table 2 in *Paper IV*, such measures could include: those that seek to minimize phosphorus losses (such as those caused by food waste), those that reduce the need for phosphorus (such as through soil testing or influencing diets away from phosphorus-intensive foods) and those that increase the uptake of phosphorus (such as through plant selection).

On the supply side, an important questions is what are the most effective means to source, recover and re-use phosphorus from the entire food production and consumption system, taking into account important sustainability criteria? Sources of phosphorus could include 'used' sources (such as excreta, food waste, crop residues) and 'new' sources (such as algae or phosphate rock). The processes for recovering and re-using phosphorus vary widely (as indicated in table 1 of *Paper IV*), and include composting, incineration and precipitation or concentration.

Part of such an analysis should include a revised peak phosphorus analysis based on improved/new data, both on production levels and importantly, the extent of remaining reserves.

Important criteria for assessing the value of any supply- or demand-side measure include: the total life-cycle energy consumption, the amounts of chemical and resource use involved, the quality and quantity of the nutrients recovered, the logistics of storing and transporting the nutrients to users, user needs and perspectives, the cost-effectiveness of both recovery and reuse, and the levels of other resource inputs. Further, there is a need to address the question of what technological changes (such as recovery infrastructure), institutional changes (such as new markets, policies and partnerships) and what social changes (such as household behavior regarding sanitation and food waste management) would be required to implement these measures.

Research recommendation 2: Improve phosphorus data accountability and transparency

Improved phosphorus data is required to contribute to: a) more reliable assessments, analyses and decisions regarding the use of global phosphorus resources, and b) more effective phosphorus governance generally. Specific mechanisms for increasing accountability and transparency (such as 'governance-by-disclosure' initiatives (Gupta, 2008)) are not recommended here as they are considered too premature for the nature of this embryonic phosphorus scarcity research. Rather, important issues for consideration in the future production and management of phosphorus data are proposed. These include:

1. **Criteria** for data accountability. Appropriate data on phosphorus is:
    - *Reliable* – accurate and consistent baseline data is sought and updated at appropriate intervals;
    - *Transparent* – assumptions behind the data and analysis are clear to users;
    - *Independent and/or trustworthy* – both the production and management of important data sets are undertaken by actors considered independent, or are reviewed/scrutinized by a third-party considered trustworthy by all stakeholders;
    - *Participatory and inclusive* – key stakeholders (beyond the fertilizer industry, such as farmers) have the opportunity to participate in knowledge production and management. For example, they can contribute to decisions about what are the most useful/appropriate data sets, in addition to increasing legitimacy and trustworthiness); and
    - *Available* – all users have equitable access to key data (see data users below).
2. Important **phosphorus data** types required:
    - All sources of phosphorus useful for fertilizer production (including but not limited to phosphate rock);
    - Annual production – compiled at various scales (global, national, regional);
    - Availability (short and long-term);
    - Current levels of recovery and re-use from different stages in the food production and consumption system;
    - Physical and biological availability of soil phosphorus and current losses from soil (see national case study);
    - Market transparency (e.g. price trends);
    - Future demand for phosphorus (for food and non-food sources); and
    - Environmental, health and ethical concerns (such as quality, contaminants, and levels of radioactivity).
3. **Objectives** of transparent and independent data:
    - To help ensure farmers have annual and long-term access to market or non-market sources of phosphorus;
    - To support national food security; and

- To provide baseline data for analysis and synthesis by scientists, policy-makers, industry and special-interest groups.

4. Target **users** of data:
   - Farmers (the main end-users of phosphorus);
   - Other phosphorus users (medical, detergent and other industries);
   - Phosphorus fertilizer producers and distributors (the 'middle men' between the mining companies and the farmers, if these industry sectors are not vertically integrated),
   - National policy-makers (to support food security policies, agricultural sector);
   - Citizens (so they can make more informed decisions about such issues as food, diet, and voting); and
   - Scientists, researchers and observers monitoring the sustainability of the resource use (ranging from environmental impacts to legitimacy of the producers).
5. Target **producers** of more reliable, transparent, independent data:
   - Phosphorus suppliers (including countries/companies that mine phosphate rock, or supply manure and other sources of phosphorus);
   - Phosphorus fertilizer distributors;
   - Third-party auditors; and
   - National governments and their agencies.

Research recommendation 3: Integrate the discourse on phosphorus security among existing research frameworks

Phosphorus scarcity is not an isolated problem (and phosphorus security not a goal which can be achieved in isolation from related issues). The phosphorus challenge is intertwined with the food system, water, energy, other nutrients, poverty and so on. Therefore, in addition to developing improved governance and management of phosphorus resources, phosphorus scarcity must also be addressed and integrated within the wider system.

A first step here would be to integrate the phosphorus scarcity (and phosphorus security) discourse within existing research frameworks related to global food security, global environmental change and resource scarcity, for example as discussed in chapter 4, including:

- GECAFS (GECAFS, 2006);
- IMAGE 2.4 (Netherlands Environmental Assessment Agency, 2006);
- Planetary Boundaries (Rockström et al., 2009b); and
- UNEP Resource Panel (UNEP, 2007b).

Given the most significant role of phosphorus is associated with food production, it is recommended that phosphorus scarcity is conceptually integrated into the global food security discourse as a matter of priority, and associated conceptual frameworks. For example, a relevant question here might be: how can sustainable food systems be designed and achieved, taking into account the goal of global phosphorus security (as put forward in section 6.3) and other equally important global environmental change drivers and issues, including climate change, water scarcity, energy scarcity and eutrophication.

In the comprehensive and integrated conception of the food system put forward by the Global Environmental Change and Food Systems (GECAFS) program (see section 4.2), the provision of food is viewed as a set of activities that facilitate the availability, accessibility and utilization of food. These activities in turn affect and are affected by socioeconomic forces and environmental change. In this framing of the global food system, phosphorus relates to multiple aspects, and would therefore need to be considered in: the production of food, allocation, purchasing power, and, acknowledging 'interactions between and within biogeophysical and human environments'.

The research focus of integrating phosphorus with other issues can also involve the identification and analysis of synergies between the various sustainable pathways for other important global goals such as global food security, energy and water security, and low-carbon futures. For example, changing diets is one social option that can simultaneously address issues related to energy, water, phosphorus and climate change. Similarly, a more technical strategy of reducing food waste in households and the retail sector can simultaneously result in economic benefits for households and municipalities, and reduce associated consumption of water, energy and nutrients.

Other important research questions relate to the impact of other external drivers on phosphorus security. This raises questions about how climate-related policies impact on phosphorus sustainability, including questions about the demand for different types of biofuels (sourced from virgin crops, organic waste or algae for example), and the demand for LiFePO4 batteries for electric vehicles.

Recommendation 4: Analysis of what structures are required for the effective governance of phosphorus

Phosphorus security cannot be achieved without addressing the current lack of effective governance highlighted in conclusion 4. Further analysis is required to determine suitable structures for improved governance. While the analytical framework of the Earth System Governance program (Biermann et al., 2009) is not intended to be normative, the five analytical problems of architecture, agency, adaptability, allocation and accountability could be used to structure an analysis. Improved governance structures to ensure phosphorus security could be assessed by principles of accountability (as above), allocation (including equitable access for farmers now and in the future), adaptability, improved agency, and coordinated institutional architecture. Regarding the issue of agency for example, the current lack of a phosphorus 'guardian' implies the need for some sort of representative body or consortium (existing or new) to facilitate and coordinate tasks to ensure the long-term sustainable management of phosphorus. To be effective and influential, such a body would need to be trusted by key stakeholders and have a sense of authority and legitimacy. Further, the tasks and outcomes of this body, such as the independent monitoring of phosphorus resources, the provision of data and the analysis of future trends, should be transparent and publicly available.

However it is important that analysis of governance structures does not segregate the social from the ecological and biophysical dimensions. The analysis could in part be guided by the first 10 sustainability criteria (that is, the 11^{th} criterion is effective governance which seeks to ensure criteria 1–10 are met). The system boundary covered by the governance structures needs to be widened to include: all actors, all sources of phosphorus, all environmental and social challenges, all sectors in the food production and consumption system and long-term time frames.

As Mitchell et al. (2006) point out, analysis is likely to have greater influence if attention is also paid to *process* and inclusion of stakeholders in the co-generation of knowledge for improved governance. For example, international stakeholder deliberation to build a platform for stakeholder dialogue could increase the research and policy outcomes by: a) reality-checking and contributing to the scenario development and analysis called for in Recommendation 1 above, b) further developing or refining the phosphorus security goals put forward in this thesis, and c) contributing to consensus-building given the current institutional fragmentation and lack of consensus among the key international stakeholders. Participatory methods to support such multi-stakeholder decision-making could be employed (such as backcasting or visualisation techniques within an action research framework).

Recommendation 5: National and/or regional phosphorus analyses

To complement and link to the analysis and improvements at the global scale, national case studies are recommended to determine context-specific issues, especially for phosphorus-vulnerable regions (that is, those that have a phosphorus pollution problem, are highly dependent on phosphorus imports, or have phosphorus-deficient soils, and/or low crop yields).

Such national analyses may need to consider the following important aspects related to phosphorus:

- Current and anticipated future dependence on phosphorus for food production (including key agricultural commodities);
- Current national food and agricultural policies, including national food security status;
- Economic importance of fertilizers (for example if agricultural exports are key to GDP);
- Current sources of phosphorus (including dependence on imports);
- Nutrient status of agricultural soils (for example surpassed critical soil levels or nutrient deficient soils);
- Current application rates of fertilizers;
- Farmer accessibility to fertilizers or fertilizer markets;
- Nutrient status of water bodies (for example, identification of eutrophication or oligotrophication problems);
- Key sources of losses of phosphorus in the food production and consumption system and their fate (for example manure from intensive livestock rearing, municipal effluent, erosion, runoff from agriculture, food processing, household waste);
- Geographical distribution of agricultural areas; and
- Geographical distribution of urban centres.

Policy recommendations

To both inform and be informed by the research recommendations, policy recommendations are proposed, based on the findings and conclusions. That is, in order to facilitate improvements in phosphorus security (as outlined above), the following policy aspects are recommended.

Effective governance will require clear roles and responsibilities and at minimum some broad consensus on key issues and goals. In order to facilitate such institutional change, there is a pressing need for an open dialogue between different stakeholder groups. As a first step, a platform for dialogue is highly recommended in which stakeholders can exchange ideas and views with the aim of developing a broad consensus. Such a platform can facilitate deliberation regarding the pertinent issues, challenges, goals, policy options and priorities surrounding sustainable phosphorus futures. Such a platform could take the form of a forum, a network, or meetings or conferences. Some priorities of the platform could include:

- Setting clear goals for phosphorus security (building on those recommended here), including instruments to implement or operationalize agreed-to goals;
- As noted in Recommendation 3, an international consortium or body for coordinating the governance of phosphorus for future food security is highly recommended. Such a consortium would need to be inclusive, accountable and trustworthy;
- Future governance structures such as policies that will need to take into consideration: a wider system boundary, criteria for long-term phosphorus security and identification of key actors, ranging from farmers with low purchasing power in areas of low soil fertility, to the fertilizer industry; and
- Clear roles and responsibilities for key stakeholders at the international level. That is, to deliberate over and clarify where the responsibility for different aspects of phosphorus security might lie. For example, what is the role of the FAO regarding global phosphorus scarcity? What responsibilities do the fertilizer industry and national policy-makers have? What role can scientific networks play?

Finally, it is recommended that phosphorus scarcity is put on the priority agenda in global food security debates alongside other critical resource scarcity issues such as water and energy scarcity. Phosphorus scarcity and phosphorus security can be integrated into existing dialogues, networks and discourses on global food security and global environmental change, including within the FAO (for example, it could be considered for inclusion as part of the mandated role of *Fertilizer Demand Strategies*), the UNEP (for example, it could be included within Agri-Food Program, or on the UNEP Resource Panel agenda) and the ESSP (specifically GECAFS, as noted earlier).

APPENDICES

APPENDIX A:

PHOSPHORUS CALCULATIONS & ASSUMPTIONS

A-1: Calculations and assumptions behind global phosphorus flows analysis

A-2: Calculations and assumptions behind future scenarios

A-3: Views on sources of phosphorus: mineral vs organic

A-4: Calculations and assumptions behind Australian phosphorus flows analysis

A-1: Calculations and assumptions behind global phosphorus flows analysis

A database of phosphorus values and assumptions related to the global food system was developed over 3-4 years. This includes parameters ranging from phosphorus concentration, mass, production, consumption, losses, recovery, etc, in phosphate rock, fertilizers, food, manure, excreta and other organic waste. Table A-I provides the elemental phosphorus content of a range of organic and inorganic material. Table A-II summarises the values and assumptions used in the final analysis for the phosphorus flows analysis through the food production and consumption system.

***Table A-I**: Comparison of phosphorus concentration is some inorganic and organic material used for fertilizers[1].*

Phosphorus-containing material	Phosphorus (% P by weight)	Source (and assumptions)
1. CHEMICAL:		
Phosphate (P_2O_5)	**0.44**	(European Fertilizer Manufacturers Association, 2000; IFA, 2009a)
2. GEOLOGICAL:		
Phosphate rock reserves	**8.5-13**	(Brink, 1977; Smil, 2000b; Jasinski, 2004; IFA, 2009a); *(according to Brink, if the % P_2O_5, exceeds 20%, then it can be termed 'phosphate rock'; according to the USGS, phosphate rock typically has 26-34% P_2O_5, however due to decreasing grade of ore, the % P_2O_5 has been declining)*
Lithosphere (upper earth's crust)	**0.08-0.12**	(Brink, 1977) (*10th most abundant element in the earth's upper crust*)
Sea floor nodules	**8.7-14**	(Brink, 1977)
3. COMMERCIAL FERTILIZERS[2]:		
phosphoric acid	**43.64**	(IFA, 2009a) *(converted from P_2O_5)*
MAP	**22.69**	(IFA, 2009a) *(converted from P_2O_5)*
DAP	**20.08**	(IFA, 2009a) *(converted from P_2O_5)*
TSP	**20.08**	(IFA, 2009a) *(converted from P_2O_5)*
SSP	**6.55**	(IFA, 2009a) *(converted from P_2O_5)*
NP	**6.6 -10.9**	(IFA, 2009a) *(converted from P_2O_5)*
PK	**3 - 13.1**	(IFA, 2009a) *(converted from P_2O_5)*
NPK	**2.2 - 10.9**	(IFA, 2009a) *(converted from P_2O_5)*
Organic P fertilizer	**10.91**	(FAO, 2006) *(typically from bone)*
Organic NP fertilizer	**5.24**	(FAO, 2006) *(converted from P_2O_5)*
4. EXCRETA & MANURE:		
Human urine	**0.02-0.07**	(Kirchmann and Pettersson, 1995; Vinnerås, 2002) *(Most of urine is composed of water, therefore very low concentrations; Calculated from urine mass and P mass, varies due to diet, hydration, climate)*
Human faeces	**0.52**	(Vinnerås, 2002)*(Calculated from average excreta mass and P mass, varies due to diet, hydration, climate)*
Human excreta	**0.35**	(FAO, 2006) *(converted from P_2O_5)*
Activated sewage sludge	**1.4**	(FAO, 2006) *(converted from P_2O_5)*
Sludge (from biogas digester)	**0.48 - 0.77**	(FAO, 2006) *(converted from P_2O_5)*
Struvite	**13 - 14**	(Hammond et al., 2007; Tilley et al., 2009)
Cow dung	**0.04**	(FAO, 2006) *(converted from P_2O_5)*

[1] This list is indicative rather than exhaustive.

[2] See List of Abbreviations for explanations.

Phosphorus-containing material	Phosphorus (% P by weight)	Source (and assumptions)
Poultry manure	**1.27**	(FAO, 2006) *(converted from P_2O_5)*
5. OTHER ORGANIC MATTER:		
FYM (Farm Yard Manure)	**0.07-0.09**	(FAO, 2006) *(converted from P_2O_5)*
Rural organic matter	**0.09**	(FAO, 2006) *(converted from P_2O_5)*
Vermicompost	**0.65**	(FAO, 2006) *(converted from P_2O_5)*
Crop residues	**0.04 - 0.33**	(FAO, 2006) *(converted from P_2O_5)*
Urban composted material	**0.44**	(FAO, 2006) *(converted from P_2O_5)*
Oil cake (by-product from oilseed processing)	**0.39 - 1.27**	(FAO, 2006) *(converted from P_2O_5)*
Meatmeal	**1.09**	(FAO, 2006) *(converted from P_2O_5)*
Bonemeal	**8.73-10.91**	(FAO, 2006) *(converted from P_2O_5)*

Table A-II*: Global phosphorus flows data related to the food production and consumption system.*

	Phosphorus flux (i.e. process between one stock and another stock)	P (MT/a)	References and assumptions
1. USED IN THE FOOD SYSTEM	Phosphate rock production	**17.5**	• (Gumbo, 2005; IFA, 2009a) • converted from P_2O_5
	Fertilizer production	**14.9**	• (European Fertilizer Manufacturers Association, 2000; Smil, 2000b; Gumbo, 2005; Jasinski, 2006; IFA, 2009a); • converted from P_2O_5; ~ 85% of phosphate rock used for fertilizers.
	Livestock feed additive production	**0.9**	• (Smil, 2000a, b); • mass balance; ~5% P demand for animal feed additives
	Mineral phosphorus fertilizer application	**14**	• (IFA, 2009a) • mass balance; consumption vs production
	Crop uptake (from soil)	**12**	• (Smil, 2000a, b); • extrapolated from % mass crop uptake
	Harvesting for food and fibre	**6.9**	• (Smil, 2000a, b); • mass balance (eg working backwards from phosphorus excreted);
	Food processing (from crops)	**3.5**	• (Smil, 2000a; Lundqvist et al., 2008) • mass balance; Smil estimate 55% kCal lost between farm and fork
	Production and consumption of animal feed	**2.6**	• (Smil, 2000a) • mass balance; estimate convert % food/feed to % P
	Food processing (from meat/dairy)	**0.6**	• (Smil, 2000a) • mass balance; estimate convert % food/feed to % P
	Food consumption	**3**	• (Jönsson et al., 2004; UN, 2007) • mass balance working backwards from P excreted; ~98% P eaten is excreted in adults
	Human defecation	**3**	• (Jönsson et al., 2004; UN, 2007; Gumbo, 2005; Steinfeld, 2004; WHO, 2006) • 1.2g/person/day (1-1.5g/person/day av)
	Animal defecation	**15**	• (Smil, 2000b) estimate

2. LOSSES	Effluent losses	**2.7**	• (Smil, 2000b; FAO, 2001) • mass balance (working backwards), 10% recovered therefore 90% lost; 50% lost to water.
	Manure runoff	**7**	• (Smil, 2000b; FAO, 2001); • mass balance from total manure – estimated % recovered
	Erosion due to fertilizers	**8**	• (Smil, 2000b; Millennium Ecosystem Assessment, 2005a) • mass balance; only fraction of applied P taken up by crops in a given year; high uncertainty, unknown soil stocks; therefore assumption about % of erosion due to fertilizers
	Crop losses	**3**	• (Smil, 2000b; FAO, 2001); • mass balance from estimate % generated and recovered.
	Post harvest losses	**0.9**	• (Smil, 2000a); • estimated from % kCal post-harvest losses and mass balance working backwards
	Food production losses	**1.2**	• mass balance from crops and meat/milk productively used minus food eaten.
3. RECYCLED	Animal manure recycled	**8**	• (Smil, 2000b); • 50% of 15MT recycled.
	Crop residues recycled	**2**	• (Smil, 2000a, b); • 40% of the 5MT crop residues returned to land
	Organic solid waste reused	**0.2**	• mass balance from waste
	Sewage recycled	**0.3**	• (FAO, 2001) • 10% estimated, high variability

NOTES:

1. All quantitative analyses in this doctoral research have used phosphorus (P) as the elemental unit (unless otherwise stated), rather than the widely used fertilizer industry convention of using phosphate, P_2O_5 (which contains 44% P).
2. Due to lack of data reliability and availability, baseline data is 2005 where possible, otherwise sourced from between 2000-2005.
3. Data is based on best available data, including the fertilizer industry data (e.g. IFA), UN data (e.g. FAOSTATS); government data (e.g. USGS); Academic data (e.g. Smil, 2000, 2002; and Gumbo 2005), Research Institutes (e.g. Stockholm Environment Institute)
4. 'Green' (1.) and 'grey' (2.) flows can to a greater or lesser extent be reduced through efficiency (e.g. improved fertilizer application practices), and influencing diets (e.g. reducing meat and dairy consumption, and over consumption).
5. 'Red' (3.) flows are potential recyclable flows, hence can be increased, thereby reducing detrimental losses to the environment (such as eutrophying water)
6. Only major flows through the food production and consumption chain are shown here. Flows not indicated due to their relative insignificance include: wild fish/animal catches, wild plant harvests, atmospheric P flows (e.g. ash or seaspray).

A-2: Calculations and assumptions behind future scenarios

1. Classifying scenarios

Table A-III: *categorisation of scenarios: probable, possible, preferred, most likely, and prospective, based on (Gidley et al., 2004)*

Scenario	*Description*
Probable	*Where are we heading?* This scenario is based on forecasting business-as-usual or 'do-nothing' scenarios. In most cases this is a 'low' scenario for rate of recovery of P and low % reduction of P demand.
Possible	*Where could we go?* This is a maximum possible scenario that could be achieved. While there are many 'possible' futures, this analysis refers to the 'highest' possible scenario for recovery rate of P and highest possible % reduction of P demand. This scenario is based on backcasting.
Preferred	*Where do we want to go?* This is a desired future situation, that takes into account both what is possible and the 10 criteria in box 1 (in *Paper IV*). This scenario is also based on backcasting.

2. Overall phosphorus demand

Figure A-I indicates some of the interrelated direct and indirect factors that are likely to affect the future demand for phosphate rock.

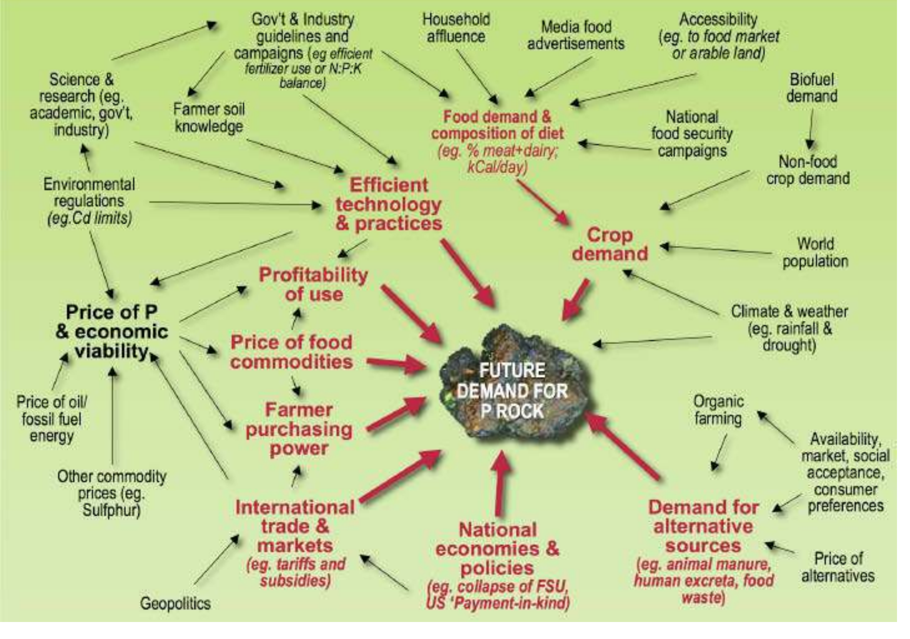

Figure A-I*: Factors affecting future demand for phosphate rock (sources: Paper I and III).*

There are no reliable, long-term forecasts for the demand for phosphorus fertilizers, beyond 5-year industry (IFA) and FAO 2015 and 2030 forecasts for mineral fertilizers derived from phosphate rock (FAO 2000). Importantly, these only consider phosphate rock on the supply side, and business-as-usual demand, hence ignore the 'silent' yet important demand from poor farmers with infertile soils who cannot currently access the fertilizer market due to low purchasing power. Table A-IV presents possible upper and lower limits for the future demand for phosphorus and a probable scenario. The probable scenario was used as the business-as-usual scenario from which demand and supply side measures were drawn in order to reduce this overall demand (described in detail in *Paper IV*).

Table A-IV*: Possible and probable scenarios for total future phosphorus demand.*

Scenario	Storyline	Estimate
Possible (high)	Demand for meat and dairy diets continues to increase globally, thereby increasing per-capita demand; the rate of biofuel crop demand continues or increases, increasing the demand for phosphorus fertilizers. Annual demand increases by 3% in 2050 and 4% in 2100.	Demand: 99.46 MT P (2050) 706.80 MT P (2100)
Possible (low)	Every person in the world receives the right amount of nutrition (no over eating or under eating) meaning a Recommended Daily Intake (RDI) of approximately 1.2g/person/day; food is produced more locally and losses from the field and food chain are minimised as far as possible (e.g. 20%); all soils reach critical phosphorus levels and fertilizer application rates only replace what is lost through harvests.	Demand: 3-4 MT P (2050) 4 MT P (2100)
Probable	Demand will continue to rise, though at rates less than the past 50 years, partly due to increased population, meat and dairy demand will continue to rise, and some demand for biofuel crops will persist, though at the same or lower per capita levels as today. Modest level of agricultural efficiency. Annual demand increases by 2% in 2050 and 0.5% in 2100.	Demand: 64.12 MT P (2050) 82.27 MT P (2100)

(Sources: Steen, 1998; European Fertilizer Manufacturers Association, 2000; Smil, 2000b; UN, 2003; FAO, 2006, 2007; UN, 2007; Heffer and Prud'homme, 2008; IFA, 2008; Koning et al., 2008)

Population projections for 2050 and 2100 based on UN medium projections (UN, 2003, 2007):

Table A-V: *World population projections (UN Medium).*

Year	Population
2005	6.49 billion
2050	9.19 billion
2100	9.1 billion

Table A-VI: *possible and probable overall phosphorus demand.*

	high possible	probable	low possible
T1	2005	2005	2005
T2	2050	2050	2050
T3	2100	2100	2100
P(T1)	26.3	26.3	29.3
R1	1.03	1.02	
R2	1.04	1.005	
P(T2)	99.46	64.12	
P(T3)	706.80	82.27	

Pt2=Pt1*R1^(t2-t1)
Pt3=Pt1*R1^(t2-t1)*R2^(t3-t2)

t1, t2 and t3 are years
Pt1, Pt2 and Pt3 are the amount of P at the different years
R1 and R2 are the growth rate of P demand in the first and second period.

3. Supply- and demand-side assumptions

Table A-VII: *Changing diets assumptions.*

Assumption	%	year
possible reduction in meat consumption	50%	2050
possible reduction in meat consumption	50%	2100
preferred reduction in meat consumption	10%	2050
preferred reduction in meat consumption	30%	2100
probable increase in meat consumption	50%	2050
probable increase in meat consumption	50%	2100

Sources: WWF, 2004; WHO, 2006b; Fraiture, 2007; Smil, 2007; Food Ethics Council, 2008; Lundqvist et al., 2008; Cordell et al., 2009a

NOTE: these % are reduced/increased P demand due to part changes in diets, and the remainder in reducing 'over-consumption' (e.g. for possible scenario, could be 33% reduction from reducing meat consumption, an the remaining 17% from reducing over-consumption+ reaching nutritional security for those under consuming-

Table A-VIII: *Food chain efficiency assumptions.*

Assumption	%
food chain losses as % of whole chain losses	50%
edible (hence avoidable) losses as % of food chain	70%
inedible (hence compostable losses as % of food chain	30%
edible losses as % of whole chain	35%
inedible losses as % of whole chain	15%
probable food chain efficiency in 2050 and 2100	-10%
possible food chain efficiency in 2050 and 2100	35%
preferred food chain efficiency in 2050 and 2100	25%

(Sources: FAO, 1999; IWMI, 2006; Lundqvist et al., 2008; WRAP, 2008)

Table A-IX: *Human excreta assumptions.*

Assumption	data	unit
RDI (Recommended Daily Intake)	1.2	g/person/day
RDI annual	0.438	kg/person/year
P in excreta - current av diet	0.438	kg/person/year
P in excreta - vegetarian diet	0.300	kg/person/year
P in excreta - meat eater diet	0.600	kg/person/year
P in excreta - 50% increase in meat diet	0.519	kg/person/year
P in excreta - 10% less meat diet	0.424	kg/person/year
P in excreta - 30% less meat diet	0.397	kg/person/year
P in excreta - 50% less meat diet	0.369	kg/person/year

Sources: *Paper I* and (National Health and Medical Research Council, 2006; WHO, 2006)

Table A-X: *Manure assumptions.*

Assumption	data	unit
manure produced - current	15	MT
manure used for fertilizer in 2005	8	MT P
possible reduction in meat consumption	50%	2050
possible reduction in meat consumption	50%	2100

preferred reduction in meat consumption	10%	2050
preferred reduction in meat consumption	30%	2100
probable increase in meat consumption	50%	2050
probable increase in meat consumption	50%	2100

Sources: *Paper I* and (Smil, 2000b, a; FAO, 2001; WWF, 2004; FAO, 2006)

Table A-XI: *Phosphate rock assumptions.*

Assumption	data	unit
P rock used for fertilizer in 2005	14.9	MT P
probable phosphate rock supply	2033	Peak year
possible phosphate rock supply	1989	Peak year
preferred phosphate rock supply	2015	Peak year
lag time for preferred change/shift to take effect	8	Years
P demand - current av diet	2.299	kg P rock/year

Sources: *Paper I* and (Gumbo, 2005; Dery and Anderson, 2007; Jasinski, 2008; IFA, 2009a)

Table A-XII: *Crop residues assumptions.*

Assumption	data	unit
crop residues produced	5	MT
crop residues reused in 2005	2	MT

Sources: *Paper I* and (Smil, 2000a, b; FAO, 2001)

Table A-XIII: *Food waste assumptions.*

Assumption	data	unit
food wasted in 2005	1.2	MT P
probable % food wasted and available for reuse	110%	of 2005 levels
possible % food wasted and available for reuse	30%	of 2005 levels
preferred % food wasted and available for reuse	50%	of 2005 levels
% reused - probable 2050	15%	of 2005 levels
% reused - probable 2100	15%	of 2005 levels
% reused - possible 2050	95%	of 2005 levels
% reused - possible 2100	95%	of 2005 levels
% reused - preferred 2050	70%	of 2005 levels
% reused - preferred 2100	80%	of 2005 levels

Sources: *Paper I* and (Smil, 2000a; WWF, 2004; Lundqvist et al., 2008; WRAP, 2008)

A-3: Views on sources of phosphorus: mineral[3] versus organic

Considering views from the literature revealed advantages and disadvantages related to different characteristics of phosphate rock and organic sources of phosphorus. Table A-XIV outlines some common perceptions from the literature.

Table A-XIV: *Common perceptions in the literature of mineral vs organic sources of phosphorus.*

Attribute	Mineral sources	Organic sources
Physical form	• Crushed phosphate rock, mineral fertilizer granules (e.g. DAP, MAP, TSP).	• Solid, liquid or slurry from manure, human excreta, crop residues, food waste.
P quality: concentration & reliability	• Can convert to high analysis (i.e. from 7% P in raw material, to 13-22% in high concentrate fertilizer).	• Bulky (usually due to moisture content); • Concentration ranges from 0.02-13%; • Quality is variable (however new development such as struvite offer ways to overcome this concern).
Potential crop yields	• High crop yields possible; • Depends on other variables such as soil quality, timing, etc.	• Variable – some argue low yields/ha, while others maintain comparable yields to mineral fertilizers.
Short-term availability	• Typically available for purchase on demand; • Typically can meet global demand (however unprecedented shortages in 2008 demonstrated the consequences of a tightness between supply and demand).	• Generated on ongoing basis (e.g. daily in the case of excreta) therefore requires some storage; • Large-scale markets currently don't exist and could not meet current demand.
Long term availability	• Non-renewable; • Despite new discoveries, average grade (% P) is decreasing and presence of contaminants is increasing.	• Renewable sources, therefore available in the long term if more efficient use.
Accessibility	• Mineral fertilizers based on mined phosphate rock are available on the international market, hence generally accessible anywhere in world; • However a lack of purchasing power, and/or tightness between market supply and demand can severely inhibit access to fertilizers as needed.	• Manure only accessible near livestock farms unless long distance transport is considered feasible; • Human excreta potentially accessible, though no large scale systems and markets currently exist; • Supply does not always meet regional demand, while in other areas, supply far exceeds demand
Timing	• 'Quick fix', fast acting, therefore productivity benefits are felt almost immediately. • However this means subsequent years also require high applications, and risks of leakage are thought by some to be increased.	• Generally slow release, therefore productivity may be slower to increase, however this contributes to longer-term productivity, and is argued as more beneficial in the longer-term.
Energy	• Energy required for extraction, production, trasport. • P fertilizers don't require as much energy to extract and process as do nitrogen fertilizers; • However the bulk of the energy cost is in the transport from mine to the farm gate.	• Due to bulkiness, transport costs ($ nutrients/km) can be relatively higher; • However this is less relevant if used locally (for example, urine can be transported 100km and still remain lower in energy cost than mining and transporting phosphate rock-based fertilizers).
Waste by-products during	• Phosphogypsum (radioactive) however this is being stockpiled and industry anticipates	• Phosphorus leakage during storage (e.g. from manure) can lead to water pollution;

[3] There are various terms used to distinguish fertilizers derived/processed from phosphate rock vs organic sources. The fertilizer industry use 'mineral' fertilizers to refer to the former, while recognising that this is not entirely accurate in all instances.

Attribute	Mineral sources	Organic sources
production	an effective way of processing may be determined in the near future.	
Possible contaminants associated with products	• Cadmium, uranium, thorium, fluoride	• Hormones, endocrine disruptors, pharmaceutical residues in urine; • Heavy metals such as cadmium, lead, mercury if mixed wastewater. • Possible plant pathogens and fungal toxins associated with application of green plant waste fertilizers.

Sources: Runge-Metzger, 1995; European Fertilizer Manufacturers Association, 2000; Johansson, 2001; Jönsson et al., 2004; FAO, 2006; IFA, 2006b; WHO, 2006a; IFA, 2007; Cordell et al., 2009a; Cordell et al., 2009b; Mavinic et al., 2009; Cordell, submitted.

A-4: Calculations and assumptions behind Australian phosphorus flows analysis

Phosphorus production and use data: mining imports/exports, domestic use, fertilizer use, food production and consumption, excreta

Table A-XV: *Data and assumptions for Australian phosphorus flows analysis.*

Phosphorus flux (i.e. process between one stock and another stock)	**P (kT/a)**	**References and assumptions**
P in domestic rock production	**220**	• (Geoscience Australia, 2007, 2008; Jasinski, 2008, 2009)
P in imported phosphate rock	**92**	• (FIFA, 2005, 2007) (ABARE, 2008; Jasinski, 2009)
P in imported fertilizers	**223**	• (FIFA, 2005, 2007; ABARE, 2008; Jasinski, 2009)
P rock to fertilizer production	**280**	• (FIFA, 2005); mass balance (imports + production - non-fert P rock)
P rock to industrial purposes	**31**	• Assumed 10% of phosphate rock use; mass balance.
P fertilizer exports	**49**	• based on domestic and imported fertilizers minus domestic use
P in fertilizer applied	**455**	• (FIFA, 2005, 2007; Geoscience Australia, 2007; ABARE, 2008; Geoscience Australia, 2008)
Net P to soils	**341**	• (CSIRO, 1998; Wakelin et al., 2004; FAO, 2006; Richardson et al., 2009) • assuming 20% take up of P from fertilizer plus 5% previous applications;
P taken up by crops (for food production)	**114**	• (CSIRO, 1998; Wakelin et al., 2004; FAO, 2006; Richardson et al., 2009) • assuming 20% take up of P from fertilizer plus 5% previous applications;
P exported in food and fibre	**85**	• (ABS, 2002; Gumbo, 2005; DAFF, 2008; FAOSTAT, 2009) • 60% food, 75% weighted by P concentration
P for domestic food industry	**28**	• (ABS, 2002; Gumbo, 2005; DAFF, 2008; FAOSTAT, 2009)
P lost in post-harvest chain	**15**	• assumption, working backwards and considering global losses and assuming 1 of this is recycled
P reaching consumer mouths	**13**	• (McLennan and Podger, 1995; Jönsson et al., 2004; FAO, 2006)mass balance • (working backwards from P in excreta and P in waste and food/fibre consumed domestically)
P in excreta	**12**	• (McLennan and Podger, 1995; Jönsson et al., 2004; Tangsubkul et al., 2005; FAO, 2006) • based on 1.2-1.5g P/person/day
P in organics recycled	**4?**	• Biosolids reused, organics (e.g. plate to paddock)(Department of Environment and Conservation (NSW), 2004; Warne et al., 2008; Zero Waste Australia, 2008) • Uncertain; Assumption; mass balance
Excreted P to waterways + landfill	**8?**	• Uncertain; assumption based on urban population; • Mass balance (from P excreted, lost) and pers comm.

NOTES:

- Remaining figures were based on material balance calculations (i.e. inputs = outputs + accumulation) by working both forwards from the start of the food chain and backwards from excretion and consumption up the chain;
- Oral information with key Australian stakeholders was also used in some instances to triangulate or compliment existing data due to a lack of publically available data and is referenced as such.

APPENDIX B:
STAKEHOLDER INTERVIEWS

B-1: Introduction letter and consent form

B-2: Interview question theme guide

B-3: Post-interview reflective questions

B-4: Horizontal stakeholder matrix

B-1: Introduction letter and consent form

The following letter was sent (in hardcopy) to targeted respondents to invite them to participate in the stakeholder interviews. The letter was tailored very slightly to refer generally to the respondent's stakeholder organisation. The consent form was provided on the back of the letter, however it was re-read, discussed and signed in person at the interview (with the exception of the first respondent who returned the consent for via mail).

Institute for Sustainable Futures

UNIVERSITY OF TECHNOLOGY SYDNEY

INFORMATION LETTER

PHOSPHORUS AND GLOBAL FOOD SECURITY

(HREC Approval number **2007-92A**)

Dear [redacted],

My name is Dana Cordell and I am a doctoral student jointly at the University of Technology, Sydney and at Linköping University in Sweden.

I am conducting research into the various dimensions of **global phosphorus supply and demand in food production** and would welcome your assistance. Your organisation has been identified as a key stakeholder in this issue, and I would therefore be grateful for your participation.

The collection of information is mainly done through interviews. Your contribution would be an interview at your workplace and should take no more than 45-60 minutes of your time. The analysis of interviews will feed into a larger analysis on the institutional and physical dimensions of phosphorus and global food security, and the results published as a PhD thesis and in publications such as journal articles.

The purpose of this research is to better understand the role of phosphorus fertilizers in sustaining global food production and consumption, in light of future trends in both food consumption and fertilizer supplies. Analysis of barriers and opportunities to the sustainable management of fertilizer sources is also of importance in this study.

This research is being undertaken as part of a PhD thesis jointly at the Department of Water and Environmental Studies at Linköping University in Sweden and the Institute for Sustainable Futures at the University of Technology, Sydney (UTS) in Australia. It has been funded by scholarships support from both the Australian Department of Education, Science and Training (www.dest.gov.au) and the Wentworth Group of Concerned Scientists, Australia (www.wentworthgroup.org).

I would propose to record the interview on audio tape for research purposes, with your permission, however all data emerging from the interview will remain strictly confidential and your personal identity would not be revealed.

You will receive a phone call in the next week to see if you are willing to participate and to arrange a time and date for the interview. You will also have an opportunity to clarify any queries you may have regarding this research.

We look forward to your involvement in this new research.

Yours sincerely,

Dana Cordell
PhD Student
Department of Water & Environmental Studies
Linköping University, SWEDEN
mobile: +46 (0) 734 438118

and

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University of Technology, Sydney
AUSTRALIA

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Associate Professor Jan-Olof Drangert
Senior Researcher
Department of Water and Environmental Studies,
Linköping University, SWEDEN

CONSENT FORM:

I have read this information letter and agree to participate in this research, by giving 45-60 minutes of my time to partake in a confidential interview conducted by Ms Dana Cordell at my workplace.

I understand that I am free to withdraw my participation from this research project at any time I wish, without consequences, and without giving a reason.

I agree that the research data gathered from this project may be published in a form that does not identify me personally in any way.

_______________________________ ____/____/____

Signature (participant)

_______________________________ ____/____/____

Signature (researcher)

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B-2: Interview question theme guide

The interview questions were semi-structured and hence did not follow a fixed questionnaire template (and indeed were tailored slightly to the specific respondent). However the general themes in which questions were explored included:

- Respondents details:
  - Respondent's position, role and background.
- Respondents views on:
  - the *sustainability* of the global food system with respect to phosphorus production and use;
  - drivers/factors influencing phosphorus *demand;*
  - drivers/factors influencing phosphorus *supply* (including different types of phosphorus – phosphate rock, manure, human excreta etc), and geographical source of phosphorus (e.g. China, Morocco etc);
  - *actors* directly or indirectly influencing the supply or use of phosphorus in the global food system;
  - *policies* or rules directly or indirectly influencing the supply or use of phosphorus in the global food system;
  - future trends (general);
  - future implications due to the finite nature of phosphate rock reserves;
  - concept of peak phosphorus;
  - different sources of phosphorus (with specific probing around views on human excreta reuse);
  - why the sustainability of phosphorus sources and usage patterns might not be on the priority agenda in the food security debate;
  - what might it take to ensure all countries and farmers have sufficient access to phosphorus fertilizers in the future (including opportunities and barriers); and
  - which actors might be responsible for managing phosphorus sustainably in the future (including possible solutions).
- Any other comments or material.
- Any related activities of the respondent's stakeholder organisation.

B-3: Post-interview reflective questions

The following questions were used internally to guide a self-reflective process regarding the interviews. I reflected on the questions immediately following each interview (e.g. in a nearby café) to ensure reflections were fresh.

Reflection questions:

Follow-ups:

Confidentiality:

____

1. *What was my general sense of how the interview went?*
2. *How may I have influenced/biased the interview?*
3. *What were the highlights?*
4. *What were the drawbacks?*
5. *What could I do better next time?*
6. *How did I feel at the time of the interview?*
7. *Any other observations?*

B-4: Horizontal stakeholder matrix

The following matrix was used to facilitate a 'horizontal' analysis, that is, to compare stakeholder views in response to the same theme or question (ie those listed in Appendix B-2). The matrix was filled with key quotes or keywords or phrases. The actual completed matrix (which resulted in 10 pages) is not shown here for reasons of participant confidentiality and research ethics.

***Table B-I**: matrix of stakeholder responses.*

THEME	Respondent 1: World phosphate rock expert	Respondent 2: Sanitation & sustainability researcher and practitioner	Respondent 3: UN fertilizer demand expert	Respondent 4: UN water sanitation and health expert	Respondent 5: International fertilizer industry expert	Respondent 6: UN environment, agriculture and food expert
Position and training	"*quote*" or *keyword/ phrase*	…	…	…	…	…
Any definition of food security?	…	…	…	…	…	…
Factors driving demand for phosphate rock?	…	…	…	…	…	…
Current system unsustainable?	…	…	…	…	…	…
Views on peak phosphorus?	…	…	…	…	…	…
Factors determining …	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…

APPENDIX C:

SOFT SYSTEMS METHOLOLGY

C-1: Rich picture of the problem situation

C-2: Application of 'TWOCAGES' mnemonic

C-1: Rich picture of the problem situation

Rich pictures explicitly acknowledge complexity and multiple interactions that can often not be readily captured in linear text (Checkland, 2001). The rich picture in figure C-1 describes my understanding in late 2007 of the problem situation, based on a literature review and my previous years of research. The initial rich picture was constructed prior to the stakeholder interviews and analysis, and, prior to the recent 700% price increase in phosphate rock and fertilizer commodities. It was initially used to inform design of the stakeholder interviews, and subsequently revised following analysis of stakeholder interviews to reflect the altered and deeper understanding of the problem situation. The rich picture here was used more for internal analysis of the problem situation (see section 3.6.1) and *Paper II* rather than communication with external stakeholders. The original rich picture was censored due to stakeholder confidentiality and research ethics.

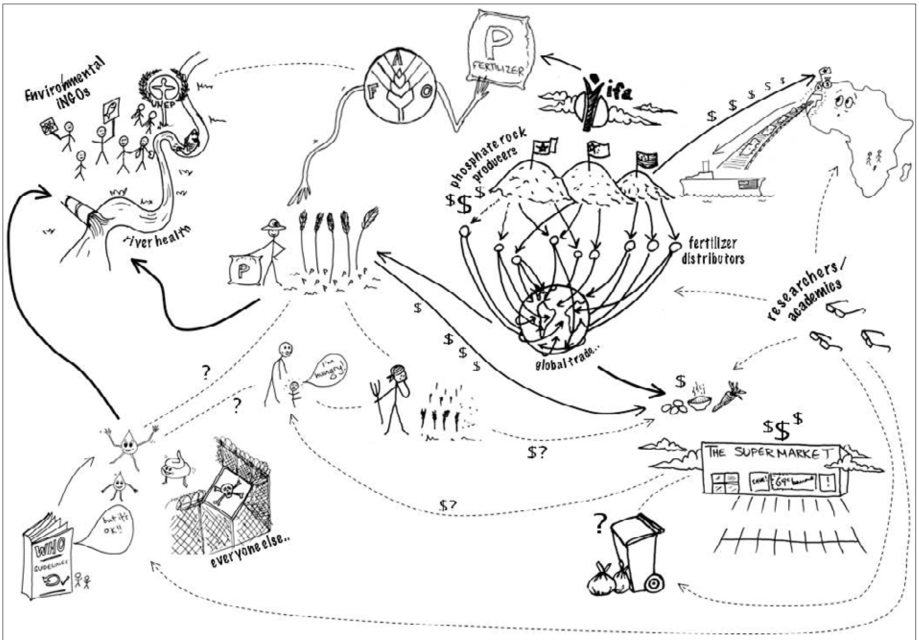

***Figure C-I**: Rich picture of the problem situation regarding the sustainability of global phosphorus resources for future food security. Bold arrows indicate perceived stronger links, while dotted lines indicate perceived weaker links. [Note: UNEP = United Nations Environment Programme, FAO = Food and Agricultural Organisation of the UN, IFA = International Fertilizer Industry Association, WHO = World Health Organisation]*

C-2: Application of TWOCAGES Mnemonic

The TWOCAGES analysis (table C-I) attempts to distil and synthesize key elements of the transformations depicted in figure 6 (*Paper II*), with the primary transformation based on the Weltanschauung of global food security. It analyses the ideal rather than current situation, for example by asking who would be the 'Guardian' of the system (Systemic Development Institute, 2008). This mnemonic was used to develop a root definition (see section 3.6.1) and in turn conceptual model. TWOCAGES is a variation of Checkland's CATWOE mnemonic (Customer, Actors, Transformation, Weltanschaaung, Owner, Environmental constraints). As noted in section 3.6.1, the TWOCAGES mnemonic was developed by staff at University of Western Sydney due to a belief that clients and students could more easily work with a mnemonic where the 'Transformation' comes first. Checkland notes that when conceptual models (figure 6 in *Paper II*) are developed and compared to the 'real world' situation, we are seeking 'accommodations' (Checkland and Poulter, 2006), rather than consensus.

Table C-I: *TWOCAGES analysis of the transformation in an ideal situation (definitions of TWOCAGES from (Systemic Development Institute, 2008; ECOSENSUS, online))*

TWOCAGES analysis		
Transformation Process	*What is the purposeful activity expressed as: input => T => output?*	The world's farmers need annual access to P fertilizers to ensure high crop yields for food production => T => Farmers needs sufficiently met.
Weltanschauung	*What view of the world makes this definition meaningful?*	Global food security and phosphorus security (means that all people have a right to food; crops need P fertilization to achieve sufficient yields (requiring external inputs to some extent); all farmers have a right to access fertilizers, the market has a limited role to play in facilitating the transformation and there is a finite nature to phosphate rock reserves.
Owner	*Who will control the proposed T? (Who could stop this activity?)*	The P suppliers, distributors and users (farmers).
Clients	*Who would be victims and beneficiaries of the T?*	Farmers, householders, P suppliers.
Actors	*Who would do the activities required to achieve T?*	P suppliers, distributors, farmers, food producers and households.
Guardian	*Proposed guardians for the community who will monitor the implementation of T and inform the owner of unintended consequences*	A non-partisan international organisation (existing or new) with a sufficient level of independence, respect from the actors (i.e. trustworthiness) and authority.
Environmental Constraints	*What constraints in its environment does this system take as given? (these are outside the control of the owner)*	High-grade phosphate rock is a finite resource; The source of P by the P suppliers and the use of P fertilizers by farmers should minimise adverse impacts on the environment and the community; Farmers have sufficient purchasing power to access sufficient fertilizers; People have enough purchasing power to access sufficient food;
System	*"List all the activities that must be initiated and coordinated to achieve T. Express this relationship in a conceptual systemic model."*	1. Obtain raw P material, 2. Convert P material to fertilizers, 3. Sell/deliver to farmers, 4. Convert to food, 5. Distribute/sell to hungry people, 6. Sanitize excreta. See figure 8 *Paper II* for conceptual model.

APPENDIX D:
STAKEHOLDER ANALYSIS

D-1: framework for stakeholder analysis

D-2: Power versus Interest matrix

D1: Framework for stakeholder analysis

A stakeholder analysis was undertaking to investigate the potential motivations and interest of each selected stakeholder, and the nature of their relationship and power to the phosphorus scarcity problem. The analysis was originally undertaken prior to the stakeholder interviews, in order to inform and enrich the interview design and the conduct of the interviews. That is, to better define how to engage each stakeholder and maximise effectiveness of the interviews.

The analysis was the revisited following the interviews, to inform further analysis and synthesis. Further, this stakeholder analysis complements (informs and is informed by) the soft systems analysis. Both were iterative and interconnected processes, although this stakeholder analysis sits within the overarching soft systems approach. For example, the stakeholders have previously been identified through the soft systems approach.

Drawing on the stakeholder analysis literature from the fields of development, systems thinking and action research (Overseas Development Administration, 1995; Dick, 1997; Checkland, 2001; Hovland, 2005) key attributes used to assess each stakeholder included:

1. Type of stakeholder:

- Private, public or civil society stakeholders?
- International, national or regional?

2. Role, mission, objectives:

- Established from their official websites and documents.

3. Weltanschauung:

- What worldview or paradigm might inform this stakeholder group? E.g. neoclassical economics, environmental activism, quantitative epidemiology etc.
- Indicate level of confidence in this attribution – from strong confidence to a best guess.

4. Overt Interests:

- Nature of interest in this problem area?
- In favour or opposed? To what degree (low, medium, high).
- Indicate level of confidence in this estimate – from strong confidence to a best guess.

5. Covert interests:

- What might be their unstated needs or interest in this area?
- Indicate level of confidence in this assumption – from strong confidence to a best guess.

6. Power:

- Level of influence and power? low, medium, high?
- Indicate level of confidence in this estimate – from strong confidence to a best guess). Nature of that power[4]?

The actual detailed assessment of each stakeholder against the above criteria is not presented here for reasons of confidentiality and research ethics.

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[4] "*Power' measures the influence they have over the project or policy, and to what degree they can help achieve, or block, the desired change*" (Hovland, 2005).

D2: Power versus Interest matrix

The analysis of perceived[5] power versus interest suggests that the most powerful stakeholders are also those that have the least interest in acknowledging phosphorus scarcity, peak phosphorus and the long-term equitable access to phosphorus resources by the world's farmers (figure D-I). These stakeholders contribute to the continuation of the market as the dominant institution governing global phosphorus resources. Figure D-I also indicates the power and interest of nations that are key actors at the international level. The analysis/assumptions are excluded due to stakeholder confidentiality and research ethics.

In this figure, 'interest' refers to the nature (+ = positive interest, - = negative interest or 0 = neutral), of a stakeholders likely interest (i.e. in favour or opposed) in seeing more attention given to phosphate scarcity and subsequent institutional change required for more sustainable governance. 'Power' refers to the stakeholders influence over the outcomes for governing phosphorus (e.g. decision-making power, political power) and the degree to which they can help achieve or block the institutional change (0= negligible power, + = some power, ++ = very powerful).

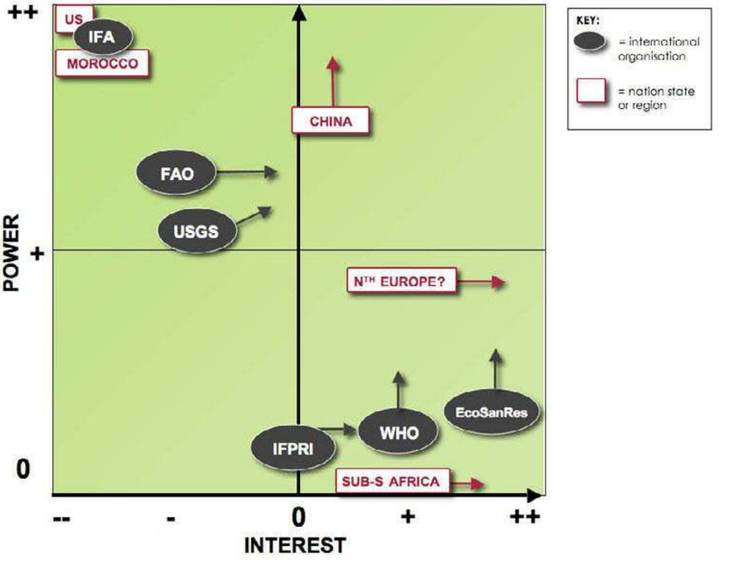

***Figure D-I**: Illustrative representation of perceived stakeholders power versus interest in supporting awareness of global phosphate scarcity, farmer accessibility to phosphate and subsequent institutional change required for improved governance of global phosphorus reserves. The arrows indicate the anticipated direction some stakeholders would move to, if any. Source: Kerschner and Cordell, 2007*

NOTE: IFA = International Fertilizer Industry Association; FAO = Food and Agricultural Organisation of the UN; USGS = US Geological Survey; IFPRI = International Food Policy and Research Institute; WHO = World Health Organisation; EcoSanRes = the Ecological Sanitation Research programme of the Stockholm Environment Institute.

In line with Actor Network Theory (Law, 1992) and indeed other institutional theories, power dynamics exist not just between international stakeholders and nations, but also between commodities and institutional norms and conventions (Bowker and Star, 1996; Vatn, 2005). Some of these are

[5] Perceived by myself, the analyst.

highlighted in Table D-1[6]. Although in a physical sense, phosphorus can be sourced from multiple organic and inorganic sources, phosphate fertilizer commodities based on phosphate rock are viewed as the superior source in modern agriculture and hence given a powerful status or meaning by some actors. Least powerful commodities include those derived from human excreta, such as urine as a ready 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. Hence it is often ascribed a least powerful status.

Table D-I: *Powerful and least powerful influences and entities in the context of phosphorus and global food security.*

Entity:	Powerful	Least powerful
Commodities	Phosphate rock, mineral fertilizers	Human excreta (especially as source separated[7] urine and faeces)
Institutions*/ paradigms	International market	Right to food
Countries/ regions	US, Morocco, China	Western Sahara, Sub-Saharan Africa, India
Actors	OPC[a], Mosaic[b], IFA[c]	Poor farmers, hungry people

* includes norms, conventions and rules; [a] Morocco's state-owned phosphate mining company; [b] largest US private-owned mining company; [c] International Fertilizer Industry Association.

[6] For simplification to illustrate the point, 'powerful' and 'least powerful' have been used as categories, where as in reality these entities are more likely to sit on a power spectrum.

[7] Source separated in this context refers to separating human excreta fractions at the source: the toilet, such as through a urine diverting toilet (Cordell, 2006).

APPENDIX E:
NATIONAL STAKEHOLDER WORKSHOP ON 'FUTURE OF PHOSPHORUS'

E-1: National stakeholder workshop methodology and structure

E-1: National stakeholder workshop: methodology and structure

To contribute to the Australian case study, a one-day, high-level national stakeholder workshop was held at the University of Technology, Sydney on 14th November, 2008. The core objectives of the workshop were firstly, to collectively vision and deliberate on sustainable future phosphorus pathways, and identify research and policy opportunities and barriers to reaching that future vision. Secondly, to share knowledge and perspectives on sustainability implications of the current approach to sourcing and using phosphorus in food production both globally and within Australia (in this way contributing to mutual-learning that was both relevant to this thesis and the stakeholders' own research and policy activities).

Inline with the action research approach taken in this doctoral research (and indeed in the Australian case study), the workshop was intended to be participatory, drawing from the collective knowledge of participants from different sectors. My core role during the stakeholder deliberation was observer, however I participated in the following ways: 1. designing and organising the workshop, 2. preparing the background research paper, 3. presenting one of the three presentation. 4. Asking the occasional open-ended question related to the trigger questions, 5. Networking during the coffee break, lunch and drinks

Stakeholders were selected based on an initial assessment of key institutional agents and their roles related to phosphorus through the Australian food production and consumption system (see figure E-I). This included stakeholders with responsibilities related to: phosphate rock resources, mining and geopolitics, fertilizer production and use, farming, crop phosphorus use, diet and health, organic solids waste recovery, nutrient recovery from wastewater and general sustainable systems. Participants represented government, industry, research and special interest groups (Cordell and White, 2009). Invited participants were sent an official invitation explaining the intentions of the workshop (see figure E-III).

Participants were provided with a discussion paper prior to the workshop (Cordell and White, 2008) and details of all stakeholder participants mapped against a conceptual diagram of phosphorus flows through the Australian food production and consumption system. This enabled participants to gain a preliminary idea of the broad and multiple roles and perspectives represented at the workshop.

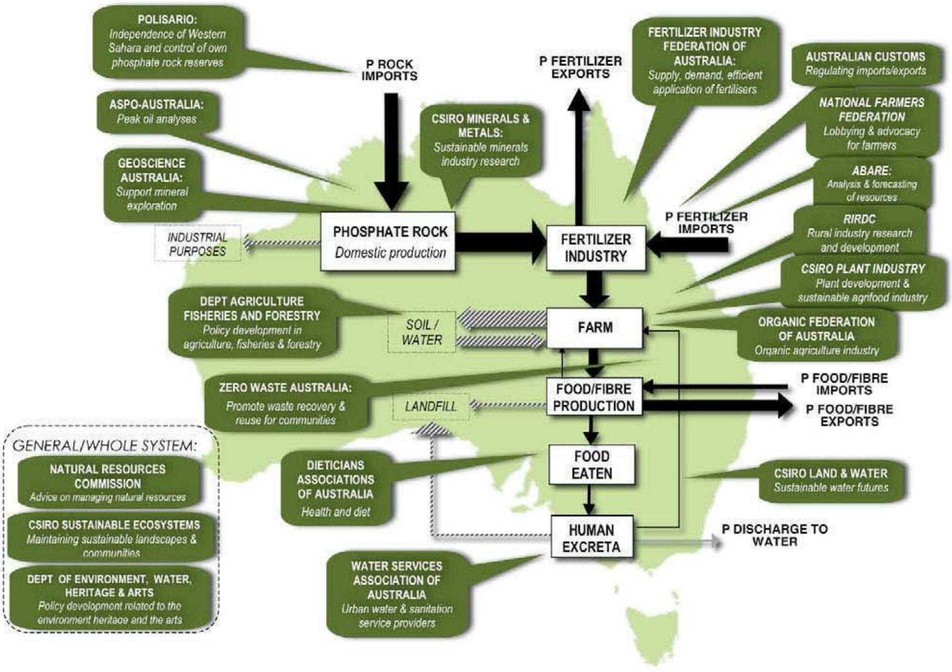

Figure E-I: *Multiple Australian stakeholders and their role related to phosphorus in the food production and consumption system. In a similar way to the global scale, none of the stakeholders identified here have as a priority ensuring long-term phosphorus availability for food production. (Note: this is not an exhaustive list of stakeholders, rather it is indicative of the institutional fragmentation of the phosphorus cycle through the food production and consumption system). Source: Created for this research.*

Following introductions, five-minute presentations covered:

1. *Global phosphorus scarcity and sustainability implications for Australia* (ISF, GPRI)
2. *Australian Fertilizer Industry: Market and Public Policy* (FIFA)
3. *Strategies for improving the phosphorus-use efficiency of Australian crops* (CSIRO Plant Industry)

Trigger questions introduced at the start of the workshop included:

- How can Australian agriculture adapt to increasing global phosphate scarcity?
- What are the implications for rural livelihoods?
- What will it mean for the environment and for the economy?
- What policy measures are appropriate for dealing with this and which sectors should be prioritised?
- Which actors are likely to play a role in a sustainable phosphorus future?
- What do we want a sustainable phosphorus future to look like in Australia?

A facilitated discussion followed, leading to participants identifying key challenges and issues for further investigation. Following a break, participants were then asked to envisage a sustainable phosphorus future in 2030 and describe the key characteristics of this vision. The visions were prepared based on backcasting a 'preferred' future, that is, working backwards from a specified preferred future to the present (as discussed in section 3.5.3). These visions were first prepared individually, then discussed in pairs and finally synthesized in a plenary discussion, leading to prioritisation of they key visions and characteristics (participants were each given 5 green dots to place next to their priority items) (see figure E-II).

In small groups after lunch, participants were asked to consider:

1. Implications and key challenges of the preferred future visions?
2. What actions would need to happen between now and 2030 in order to meet the visions?

A plenary discussion then clarified and prioritised these research, policy and technical actions, identifying potential responsible sectors. Finally, a wrap up session then distilled some concrete actions that the group could take, followed by an evaluation of the workshop. Drinks and mingling continued informal discussions after the workshop formally closed.

The outcomes of the workshop are provided in the Synthesis Report (Cordell and White, 2009) and summarised in *Paper V*. An individual evaluation of the workshop indicated a high level of participant satisfaction, including that one positive outcome of the workshop was the brining together of a disparate group of stakeholders to discuss the topic of phosphorus scarcity. Many participants were keen to continue discussion and action on policy and research on the topic.

***Figure E-II**: photos from the National stakeholder workshop.*

Figure E-III: *National stakeholder workshop invitation sent to identified stakeholders.*

THINK. CHANGE. DO

INSTITUTE FOR SUSTAINABLE FUTURES

ISF: NATIONAL WORKSHOP

THE FUTURE OF PHOSPHORUS

Institute for **Sustainable Futures**

UNIVERSITY OF TECHNOLOGY SYDNEY

THE FUTURE OF PHOSPHORUS

IMPLICATIONS OF GLOBAL FERTILISER SCARCITY

Background

All modern agricultural systems are dependent on continual inputs of phosphate fertilizers derived from phosphate rock. Yet phosphate rock is a non-renewable resource and current reserves may be depleted this century. The market price of phosphate rock has risen 700% in just 14 months. Unlike water, oil and even nitrogen, phosphorus receives little attention in the policy debate on securing the world's food production, yet without it we cannot produce enough food at today's production yields. There is no substitute for phosphorus in food production.

Australia has some of the world's most naturally phosphorus deficient soils and yet we invest heavily in phosphorus demanding export industries, like beef, wheat and wool. So Australia's agriculture depends heavily on the continuing importation of phosphate rock for fertilizers. At the same time phosphorus reaching our waterways from agricultural runoff and sewage effluent is causing algal blooms, and a significant proportion of phosphorus is lost in food waste.

A substantial gap exists in both the research to understand the whole phosphorus cycle through the food production and consumption system and policies to address the emerging global phosphorus scarcity problem.

The workshop

This workshop will present the latest global research on the phosphorus situation and the implications for Australia. A participatory discussion of potential future pathways to sustain Australia's use and management of phosphorus resources in light of global trends will follow.

Date: **Friday 14 November 2008**

Time: **9.00am - 3.00pm**
Morning tea, lunch & afternoon tea will be provided

Venue: **ISF board room, Level 11, 235 Jones Street**

Map: http://www.isf.uts.edu.au/contact/index.html

RSVP: **Lucy.Hall@uts.edu.au or phone 02 9514 4943 by Monday 1 September.**

On registration you will receive a workshop package, including a discussion paper on the key science and policy issues for the Australian context, a list of other participants and a program for the workshop.

The workshop will be hosted by the Institute for Sustainable Futures (ISF), a research and consulting organisation at the University of Technology, Sydney. The workshop forms part of ongoing research being undertaken jointly by ISF and the Department of Water and Environmental Studies at Linköping University in Sweden.
The Global Phosphorus Research Initiative: www.phosphorusfutures.net

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GLOBAL PHOSPHORUS RESEARCH INITIATIVE

APPENDIX F: PARTICIPANT-OBSERVATION

F-1: Key observations

F-2: Key participation: contributions to 'situation' outcome spaces

F-3: Selected citations in scientific and professional publications

F-4: Communication matrix

F-5: Global Phosphorus Research Initiative website

F-1: Key observations

The following describe some of the key global interlinked events and changes I have observed that directly relate to the field. As noted in section 3.4.1, data sources for real-time information included daily *Google Alerts* for official news, reports, website and blog containing any of the key words "phosphorus", "peak phosphorus", "fertilizer" and "fertiliser". As the food crisis unfolded, often 10-30 alerts were received on a daily basis. Other data sources including periodic monitoring of journals and key stakeholder websites for new publications or position statements, and a growing network of researchers and practitioners who on send information. Some key observations included:

- ***Price of phosphate rock spikes***: Since January 2007, the price of phosphate rock rose 700%. This has in turn raised the price of phosphate fertilizer commodities, shocking farmers and other phosphorus users.

- ***Global food crisis emerges***: The global food crisis materialized, leading to doubling of staple food commodities like rice and wheat. This resulted in food riots, in addition to increasing food insecurity. Whilst the price of fertilizers can lead to an increased price of food, it is likely that the recent fertilizer price spike has not actually affected food prices yet, though may do so when the current crops fertilizers with 'expensive' fertilizers are harvested and processed. However the price of fertilizers can be absorbed by the farmer and therefore not passed on to the consumer.

- ***Oil price spikes***: The third oil price shock occurred in 2008, sending the price of oil over $140/barrel. This has in-turn affected the discussions and demand for biofuels, which in-turn increases the demand and price of phosphate rock. The price of oil also has implications for the 'farm-gate' price of phosphate fertilizers because phosphate rock mining, processing and especially transport (typically freight) of phosphate rock and fertilizers is heavily dependent on oil and hence the price of oil.

- ***Peak oil framing gains traction***: The concept of peak oil is gaining traction in more mainstream spheres. For example the International Energy Agency Chief Economist stated in a noteworthy interview in November 2007: "*if we don't do anything very quickly, and in a bold manner, our energy system's wheels may fall off – within the next seven years*" (Financial Times, 2007).

- ***'Peak phosphorus' framing emerges***: The concept of 'peak phosphorus' is posted on Energy Bulletin website (dedicated to peak oil and other resource issues). Whilst this is not a peer-reviewed paper, it is internet-based, and has a wide distribution. The number of citations of peak phosphorus rises from zero in June 2007 to over 3000 in June 2008.

- ***China increases export tariff***: One of the world's largest phosphate producers, China, imposes a 135% tariff on exports that effectively halts exports from the region over night. This pushes phosphate prices up.

- ***Phosphate rock price peaks***: The price of phosphate rock peaks at US$431/tonne in September 2008 (see figure 5-16 in section 5.6).

- ***Regions respond to price spikes***: In addition to substantial increase in media on the phosphorus problem (including peak phosphorus and phosphorus scarcity), Some regional responses to the sudden increase in phosphate and fertilizer price spikes (from 2008 onwards) include:
    - Senate inquiry in Australia into pricing structures and potential market distortions (e.g. Oligopolies and Cartels),
    - Fertilizer rationing in India (and other countries), followed by riots and even farmer suicides;

    - Nutrient Flow Task Group established in the Netherlands as a partnership between industry, academia and government; and
    - The European Commission issues an Invitation to Tender for "Sustainable Use of Phosphorus".

- ***International Conferences discuss phosphorus scarcity***: Scarcity of global phosphorus resources is mentioned at prominent international conferences, including:
    - *World Water Week* (August, 2008) closing ceremony mentions scarcity of mineral phosphate;
    - Global phosphorus scarcity is a key theme in opening plenary session (and throughout) the *International Conference on Nutrient Recovery form Wastewater Streams* (Vancouver, May 2008).

- ***Global Financial Crisis impact***: The price of phosphate rock plummets, partly due to the impact of the global economic downturn and farmers holding off purchasing fertilizers.

F-2: Key participation: contributions to 'situation' outcome spaces

The following describe the key events or ways I have directly or indirectly participated in the real-world context between 2006-2009:

- ***Phosphorus scarcity largely ignored***: Little acknowledgement of a phosphorus problem observed when engaging scientists/researchers at international conferences and workshops (August 2007). E.g. at World Water Week 2007, one fellow scientist rationalised: "*if this were such a problem I would have heard about it by now*".

- ***Stakeholder interviews conducted***: Undertake international stakeholder interviews around Europe (Sept 2007). Some interest in the phosphorus problem is sparked even among those not interviewed.

- ***Media coverage commences***: First interviewed for an article in *The Australian* March 2008, resulting in further interviews and subsequent article in the London Times, which was in-turn published again in The Australian. The initial Australian article also sparked interest by Australia's ABC National Radio program ('Bush Telegraph') which aired on 20th June 2008. Both the Times article and the Radio interview were subsequently posted on the Energy Bulletin's website, in addition to the Linkoping University homepage (See Appendix F-3).

- ***Distribute P '2-pager' while networking***: Networking at academic conferences with preliminary findings at hand (April 2008). Such as through poster presentations, networking and handing out the Information Sheet 1: "*8 reasons why we need to rethink the management of phosphorus resources in the global food system*". E.g. after talking to a prominent keynote speaker about phosphorus scarcity prior to her speech, she mentioned the issue during speech (and let me know afterwards).

- ***Citations in professional publications commence***: First citation - referred to in a pending report to FAO on Drivers of GEC on subsistence SES. Numerous citations follow (e.g. see list in Appendix F-3).

- ***Global Phosphorus Research Initiative (GPRI) formed***: Co-found the 'Global Phosphorus Research Initiative' (GPRI) in mid-2008 to formalise the joint arrangement between the Institute for Sustainable Futures at UTS and the Department of water and environmental studies at Linkoping University, and increase discussion, outreach and networking regarding phosphorus scarcity.

- ***GPRI website launched***: Create and host the GPRI website (www.phosphorusfutures.net) for the dissemination, networking on related phosphorus research. While the site was uploaded on May 2008, it was officially launched in July 2008 through the ISF monthly newsletter. The web-address was also emailed to our networks.

- ***'Real-world' citations in popular material***: While academic citations and contributions are important, change creation towards sustainable futures also happens through more informal societal channels. Popular citations of this doctoral research in such channels include media (as noted above), internet sites (e.g. Wikipedia) and institutional blogs (e.g. Australian Stock Forum). Such informal channels can be extremely effective for rapid dissemination of new ideas.
- ***Citations in professional publications continue***: Citations in more formal, professional scientific, governmental, industry publications continued (ongoing from mid-late 2008). Some of these are listed in Appendix F-3.
- ***National Phosphorus Stakeholder Workshop***: Due to opportune timing to engage key stakeholders in Australia in addressing the phosphorus problem situation, I organised and hosted a National Phosphorus Workshop in November 2008 (as described in detail in Appendix

E);

- ***Peer-reviewed journal article on peak phosphorus published***. After 942 days since initial submission, *Paper I* on global phosphorus scarcity is published in Global Environmental Change in February (the first peer-reviewed paper on peak phosphorus).
- ***High-profile public lecture***: In February 2009 I had the opportunity to co-organise and speak in the high-profile UTSpeaks public lecture series, attracting an unprecedented crowd for this event of 430 people. The lecture was filmed and aired on ABC2 TV twice and radio national once (April/May 2009);
- ***Invitations to speak at international conferences***: By early 2009, invited to present at international industry, academic and community-group conferences (e.g. in one was placed as 1st speaker, quoted in several other presentations and asked to sit on expert panel).
- ***Paper I in 'ScienceDirect TOP25 Hottest Articles'***: Indicating the growing scientific interest in global phosphorus scarcity and its link to food security, *Paper I* is listed as 2nd most downloaded article in journal of Global Environmental Change (for the period April-June 2009), next to articles on climate change, adaptation, vulnerability, resilience etc.

F-3: Selected citations in scientific & professional publications

The following are selected government, industry and scientific professional publications that have cited my doctoral research (either citation of journal articles and other publications, or via direct interviews):

1. Citations in government and inter-governmental publications:

European Commission (2008), *2nd SCAR foresight exercise - New challenges for agricultural research: climate change food security rural development agricultural knowledge systems*, Directorate-General for Research, Food, Agriculture And Fisheries, And Biotechnology, Brussels. ftp://ftp.cordis.europa.eu/pub/fp7/kbbe/docs/scar.pdf

Scottish Ministry (2008), *Report of the Food Security Taskforce*, Edited by John Scott MSP, Shadow Cabinet Secretary for Rural Affairs & the Environment, September 2008. www.scottishconservatives.com/downloads/Food_Security_Report.doc

NSW Department of Primary Industries (2008), *Sources of P other than the rare rock*. Agriculture Today, p.2, November 2008.

The Broker (2009), *The next inconvenient truth: Peak phosphorus*, Issue 15, August 04, 2009, by Arno Rosemarin, Gert de Bruijne and Ian Caldwell, http://www.thebrokeronline.eu/en/articles/Peak-phosphorus

2. Citations in scientific and interest group publications:

Nature (2009), *The Disappearing Nutrient*, by Natasha Gilbert, NATURE News Feature, vol 461, 8 October 2009, pp.716-718, http://www.nature.com/news/2009/091007/full/461716a.html

Fischer, R. A., Byerlee, D. & Edmeades, G. O. (2009), *Can technology deliver on the yield challenge to 2050*?, Expert Meeting on How to feed the World in 2050, Food and Agriculture Organization of the United Nations, 24-26 June 2009, Rome.

Harvey, D. (in press), *Energy and the New Reality: Facing up to Climatic Change*, Volume 1: Energy Efficiency and the Demand for Energy Services, EARTHSCAN (UK), Spring 2010, London.

Richardson, A. E. (2009), *Regulating the phosphorus nutrition of plants: molecular biology meeting agronomic needs*. Plant and Soil, 322, 1-2, pp.17-24.

Jensen, E. S. (2009), *The role of organic food systems in meeting future challenges in the Nordic region*, 1st Nordic Organic Conference, 18–20 May 2009, Göteborg, Sweden, http://www.nordicorganic.org/NOC-report-web.pdf#page=10

Hopper, S. D. (2009), *OCBIL theory: towards an integrated understanding of the evolution, ecology and conservation of biodiversity on old, climatically buffered, infertile landscapes*. Plant and Soil, 322, 1-2, pp.49–86.

ETC Group (2009), *Who Owns Nature? Corporate Power and the Final Frontier in the Commodification of Life*, ETC Group, Issue #100, 2009, www.etcgroup.org/upload/publication/pdf_file/707

Hinsinger, P., Brauman, A., Devau, N., Gerard, F., Jourdan, C. & Cadre, E. L. (2009), *Rhizosphere processes: the roots of ecological intensification of agroecosystems*. The Proceedings of the International Plant Nutrition Colloquium XVI, University of California, Davis, Paper 1439, http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1439&context=ipnc/xvi

Greenpeace Research Laboratories (2009), *Defining Ecological Farming*, by Reyes Tirado, Greenpeace Research Laboratories Technical Note 04/2009, Exeter, http://greenpeace.to/publications/Defining-Ecological-Farming-2009.pdf

Mishima, S., Endo, A. & Kohyama, K. (2009), *Recent trends in phosphate balance nationally and by region in Japan.* Nutrient Cycling in Agroecosystems, DOI 10.1007/s10705-009-9274-7.

Naturvetare (2009), *Brist på fosfor kan leda till svält*, (translation: *Lack of phosphorus can lead to starvation*), p.24-27, Naturvetare NR7 2009, by Marita Teräs, http://www.naturvetarna.se/sv/VETENSKAP/Medlemsartiklar/Brist-pa-fosfor-kan-leda-till-svalt/

Future Orientation Magazine (2009), *Its Not Just Oil*, Global futures, FO 6/2008, by Jeffrey Scott Saunders, Copenhagen Institute for Futures Studies www.fo-online.dk

The International Mycorrhiza Society (2009), *Sustainable phosphorus futures - A major issue*, The International Mycorrhiza Society, Vol 4, February 2009, http://www.mycorrhizas.org/docs/newsletters/NEWSLETTER_2009_FEBRUARY.pdf

Nutrient Flow Task Group (2009), *Phosphorus Depletion: The Invisible Crisis,* http://phosphorus.global-connections.nl/sites/phosphorus.global-connections.nl/files/file/Phosphorus%20Depletion%20-%20The%20Invisible%20Crisis(5).pdf

Energy Bulletin (2008), *Peak phosphorus: Quoted reserves vs. production history*, by James Ward, August 26th, http://www.energybulletin.net/node/46386

The Ecologist, (2010), *Peak phosphorus: our most important nutrient running out*, by Ewan Kingston, 12th January, 2010, http://www.theecologist.org/investigations/food_and_farming/396851/peak_phosphorus_our_most_important_nutrient_running_out.html

The Why Files (2008), *Phosphorus: Running low of an essential fertilizer?,* by David Tenenbaum, 11th September, 2008 http://whyfiles.org/286shortages/index.php?g=2.txt

Planet Ark (2007), *Prospecting the Future of Recycling*, A discussion report by Planet Ark. 2007. http://recyclingweek.planetark.org/documents/doc-76-prospecting-report-2007.pdf

Linköping University Magazine (2009), *Lack of phosphorus threat to global food production*, by Lennart Falklöf, Nr 2, 2009 International Edition, p24-26, http://www.liu.se/forskning/reportage/phosphorus?l=en

Western Sahara Research Watch (2008), *Peak P*, 22nd July 2008 http://www.wsrw.org/index.php?parse_news=single&cat=128&art=837

Permaculture Research Institute of Australia (2008), *Phosphorus Matters: Part One: Closing the Phosphorus Cycle*, by Marcin Gerwin, http://permaculture.org.au/2009/01/14/phosphorus-matters/

Other scientific and professional citations will be available at: www.phosphorusfutures.net.

3. Citations in industry publications:

Australian Farm Journal (2009), *Peak Phosphorus in sight: More effective use will extend world availability*, Part 1. By Sue Cartledge, Australian Farm Journal, June 2009, p22-24

Australian Farm Journal (2009), *Peak Phosphorus: Reducing demand for phosphate fertilizers*, Part 2. Sue Cartledge, Australian Farm Journal, July 2009, p6-8.

Centre Européen d'Etudes sur les Polyphosphate (2009), *Peak Phosphorus?,* p.13, SCOPE Newsletter – n° 73 April 2009, http://www.ceep-phosphates.org/Files/Newsletter/ScopeNewsletter73.pdf

The Organic Way Magazine (2009), *A new global challenge for food security: Peak Phosphorus*, by Dana Cordell, Food Security Feature*,* Issue 2**,** pp.10-12.

Landmark (2009), *Peak Phosphorus: A more important peak than oil?*, Landmark magazine, By Diane

Cummins, p.6-8. June, 2009, http://phosphorusfutures.net/files/Landmark_2009_Peak%20Phosphorus.pdf

Feedback Magazine (2010), The Future of Phosphorus, Meat and Livestock Australia January/February 2010

CHOICE Magazine (2009), *Phosphate fertiliser depleting: The gradual depletion of phosphate fertiliser*, crucial for mass food production, puts its future in doubt, CHOICE Magazine, 28th April, 2009, www.choice.com.au/goArticle.aspx?ID=106840

The Land, (2008), *Next, a phosphate crunch?* Richard Fox, The Land, 18th December 2008.

4. International & national media coverage:

London Times (2008), *Scientists warn of lack of vital phosphorus as biofuels raise demand*, by Leo Lewis, The Times, 23rd June, 2008, http://www.timesonline.co.uk/tol/business/industry_sectors/natural_resources/article4193017.ece

The Australian (2008), *Warning of World Phosphate Shortage*, by Mathew Warren, The Australian, 12th March, 2008, http://www.theaustralian.news.com.au/story/0,25197,23360117-30417,00.html

ABC Radio National (2008), *The era of peak phosphorus is coming*, ABC Radio National, Bush Telegraph, 20th June, 2008 http://phosphorusfutures.net/files/PeakP_ABC_radio_interview.mp3

South China Morning Post (2008), *A matter of social duty and fertiliser*, Ivan Broadhead, p.12, Sunday Morning Post, August10, 2008 http://www.wsrw.org/files/pdf/scmp_10.08.2008.pdf

The Globe & Mail (2009), *The sewage plant carries the sweet smell of valuable phosphorus*, The Globe & Mail (Canadian national newspaper), May 18th, 2009.

The Financial Review (2009), *New Skills to cope with a wider world*, 2009, Australian Financial Review, 18 September 2008

ABC TV (2009), *The Story of Phosphorus, in Eating the Earth*: ABC Fora, ABC2 Television, 9th April, 2009 http://www.abc.net.au/tv/fora/stories/2009/04/09/2539410.htm

Weekly Times (2009), *Soil quality in crisis*, Peter Hunt, September 21, 2009 http://www.weeklytimesnow.com.au/article/2009/09/21/113681_on-farm.html

Le Monde (2010), *Des experts redoutent une pénurie de phosphates d'ici à la fin du siècle*, Bertrand d'Armagnac, 11th January, 2010

Other media coverage is available at:
http://phosphorusfutures.net/index.php?option=com_content&task=view&id=23&Itemid=36#GPRI_in_the_News

F-4: Communicating transdisciplinary research to multiple audiences

To aid effective and strategic communication of this doctoral research to multiple and broad audiences, a stakeholder matrix was developed. All important audience groups were first identified, ranging from international organisations, industry, public interest groups, academic peers, other scientific peers. For each identified audience, seven questions were answered (in the table column heading in table F-I below). The actual analysis cannot be shown for confidentiality reasons. The communication analysis was used during engagement of the audiences in the latter part of the doctoral research (e.g. for use during conference presentations, this thesis, meeting, media etc).

Table F-I: *Strategic communication matrix for communicating to multiple audiences.*

Audience	Why are they important?	Their likely overt or covert agenda	Implications of communicating with them	Implications of not communicating with them	Language to use	Language to avoid	How to communicate/ component
Audience 1							
Audience 2							
Audience 3							
….							
….							
Audience 13							

Language and framings: contentious terms

Through participation in the problem situation and context (as described in Appendix F-2), including the in-depth stakeholder interviews, it became apparent that various terms were contentious and held specific and at times unhelpful meaning to certain powerful and influential actors. For example, some perceived the term “running out” of phosphorus to be inappropriate and misleading because the world will not physically run out of the element phosphorus. To ensure effective communication of this research to multiple audiences while ensuring scientific integrity, an analysis of potentially contentious terms was undertaken in order to identify which terms to avoid and which to favour, including identification of stakeholder responses to those terms.

The following terms were identified and analysed (this cannot be shown due to confidentialities):

- Running-out
- Scarcity
- Supply
- Peak
- Problem
- Perceived problem-situation
- Accessibility
- Availability
- Sovereignty
- Security
- Sustainability
- Crisis

This resulted in the adoption of the term *phosphorus scarcity* as the most appropriate framing of the problem situation and *phosphorus security* as the most appropriate framing of the preferred future situation.

F-5: Global Phosphorus Research Initiative website

Figure F-I provides a snapshot of the homepage of the Global Phosphorus Research Initiative website (as at 7/8/09).

Figure F-I: *snapshot of Global Phosphorus Research Initiative homepage (www.phosphorusfutures.net)*

APPENDIX G:
QUALITY IN TRANSDISCIPLINARY RESEARCH

G-1: Quality criteria

***Table G-I**. Interpretation of criteria for interdisciplinary (ID) and transdisciplinary (TD) research and suggested modified forms of these criteria (Mitchell and Willetts, 2009)*

Criteria based on the literature on doctoral-ness and examiners views	***Key points about what it means for ID and TD research***	***Modified form of criteria (closer to how it might be appropriately interpreted for ID and TD research)***
Substantial contribution to knowledge	• 'knowledge' needs to be interpreted broadly • contributions toward, or impact of the research context, situation, area of work and practice need to be included (which relates to socially robust knowledge in the problem space) • the adjective 'substantial' may be misleading, more important that the student articulate the nature of the contribution and its significance	**Original and creative contribution to knowledge and/or practice**
Well designed and coherent argument	• critical criterion for ID and TD research for demonstrating validity of the research and providing strong synthesis across diverse areas • requires an authentic voice of the researcher to come through • may include aware [in]coherence for dealing with paradoxes likely to arise in ID and TD research	**Critically aware, coherent argument**
Engages with literature of appropriate breadth and depth	• balancing breadth and depth is important, depth (even in new areas) must always be sufficient to allow appropriate use for the purpose at hand • developing and justifying critique outside one's core discipline is challenging and yet essential • engagement beyond literature (with artefacts or societal perspectives/problem situation) is important • the need for strong synthesis across different areas is strong	**Critical, pluralistic engagement with appropriate literature, artefacts, the research context and multiple stakeholder perspectives within it**
Evidence of critical reflection	• critical criteria in determining the calibre of an ID or TD doctorate, as it is essential to developing an awareness of one's own epistemology and engaging respectfully with diverging views inevitably encountered in ID and TD research • may be explicitly or implicitly discernable in the final doctoral work	**Evidence of critical reflection/reflexivity on own work**
Grasp of theoretical perspectives or grasp of methodology	• requires evolving development of a methodology to align with the underlying theoretical perspective and methods used • requires a critical understanding of methodologies from different fields to enable a student to justify research design choices.	**Alignment between epistemology, theory, methodology, claims, and enquiry space**
Mastery of topic	• challenging and potentially impossible with respect to the topic • mastery in the approach taken, or through influence and application are more relevant and important	**Mastery of the process and/or outcomes**
Effective and well-finished presentation	• requires use of multiple languages and effective approaches to communicate across disciplines	**Effective communication for diverse audiences**

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