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Anna Kuokkanen

UNDERSTANDING COMPLEX SYSTEM CHANGE FOR A SUSTAINABLE FOOD SYSTEM

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium of the Student Union House at Lappeenranta University of Technology, Lappeenranta, Finland on the 14th of December, 2016, at noon.

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Abstract

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This thesis investigates a complex system change for navigating food systems towards sustainability. The thesis employs interdisciplinary theoretical framework, grounded in the dynamics of a complex adaptive system. In particular, the two most prominent research directions, social-ecological-system research and socio-technical-system research, are adopted for the generation of analytic and normative research aims. Four distinct but complimentary research questions are raised in order to gain more comprehensive understanding of sustainability change in the food system.

The results highlight the role of food systems in disrupting ecosystem services, namely nutrient cycles, on both global and local scales. Critical planetary thresholds have been transgressed so significantly that they set more stringent limits to future food security than availability of resources and population growth. Radical and simultaneous transformations across the food systems are imperative, for single shifts, such as preventing all food waste and losses and adopting a vegan diet across the globe, alone are not sufficient to bridge the gap and maintain food security for all. Yet tentative and highly controversial, planetary boundaries operationalize ecosystem service based approach to sustainability and the existence of limits to environment's functions critical to human wellbeing.

Including temporal and bottom-up assessment of nutrient boundaries provides important insights about the cross-scale dynamics in social-ecological systems that are dismissed if only global scale is considered. Firstly, the local boundaries in Finland are more stringer than the global boundaries due to the sensitivity of the Baltic Sea. Secondly, historically cumulated nutrient use in Finland and Ethiopia demonstrate the disparity of transgressing nutrient boundaries and the striking inequality in access to nutrients. In Finland nutrient boundaries are transgressed due to high inflow of nutrients, while in Ethiopia they are transgressed due to high outflow of nutrients due to erosion. Thus bridging the current sustainability gap requires a simultaneous reduction of inequality and redistribution of productive assets, not only virgin nutrients but also those that have accumulated in Finnish soils and water bodies.

Socio-technical approach to sustainability change highlights that regime transition is often constrained by systemic resistance due to the prevalence of lock-in dynamics. Food system locking into unsustainable nutrient economy emerges through mutually reinforcing increasing returns processes in production, consumption and institutions.

This calls for active and deliberate regime destabilisation, not least by means of food system policy, bridging consumption to production, and thus involving those actors and practices that are the most influential at present. Simultaneously though, caution of creating and enabling the situations for new lock-ins is warranted. Furthermore, sustainability transitions can be linked to the broader policy level by analysis of market, structural and transformational failures. Stimulation of system innovation in the food system requires attention foremost at the prevailing structures and practices through re-assessing several sectoral policies, at least agriculture, environment, energy and waste policies, and their coherence and directionality. Policies cutting across several sectors are essential, but they require not only changes in institutions but also meaningful interaction and cooperation.

Keywords: complex adaptive system, sustainability change, social-ecological system, socio-technical system, resilience, sustainability transition, food system, nitrogen, phosphorus, nutrient economy, system innovation

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The process that culminates to this thesis was both longer than the official count, 3 years and approximately 9 months, and broader than what these 84 pages entail. To be precise it started sometime in spring 2010 with summer job interview and the first terms of reference at LUT. Although much sweat, tears, anger, frustration, desperation and coffee has been put into this piece of work, I would argue that these pages do not live up to the total sum of all the learning that accumulated throughout this time.

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I feel privileged for the learning so far, and hence indebted to not quit here..

Anna Kuokkanen
December 2016
Lappeenranta, Finland

To solidarity, diversity and idleness

Contents

List of publications

This thesis is based on the following papers. The rights have been granted by publishers to include the papers in dissertation.

I. Kahiluoto, H., Kuisma, M., Kuokkanen, A., Mikkilä, M., Linnanen, L. (2014). Taking planetary nutrient boundaries seriously: Can we feed the people? *Global Food Security*, 3(1): 16-21. (Collection of literature and data)

II. Kahiluoto, H., Kuisma, M., Kuokkanen, A., Mikkilä, M., Linnanen, L. (2015). Local and social facets of planetary boundaries: right to nutrients. *Environmental Research Letters*, 10: 104013. (Collection of literature and data)

III. Kuokkanen, A., Mikkilä, M., Kuisma, M., Kahiluoto, H., Linnanen, L. (2017). The need for food system policy to address nitrogen and phosphorus lock-in. *Journal of Cleaner Production*, 140 (Part 2): 933-944. (Principle author and investigator)

IV. Kuokkanen, A., Mikkilä, M., Kahiluoto, H., Kuisma, M., Linnanen, L. (2015). Not only peasants' issue: Stakeholders' perceptions of failures inhibiting system innovation in nutrient economy. *Environmental Innovation and Societal Transitions*, 20: 75-85. (Principle author and investigator)

Nomenclature

Abbreviations

CASs	Complex-adaptive systems
N	Nitrogen
N_r	Reactive nitrogen
P	Phosphorus
PBs	Plantery Boundaries
SES	Social-ecological system
STS	Socio-technical system

1 Introduction

Concerning global sustainability, various scholars have contended that we are facing not just one discrete problem, but rather a complex set of 'Grand Challenges', which range from resource depletion, to climate change, to growing food insecurity and to a widening inequality gap (Reid et al., 2010). Many of these challenges are actually intertwined and share a common basis of origin: an ignorance of global environmental change mechanisms and a fundamental inability of economic, political, management, and (even) scientific systems to deal with the complexity (Gallopin et al., 2001; Walker et al., 2009). What makes the current environmental changes so alarming is the fact that they are induced by human activities and that they are occurring at a pace never experienced before (Berkes et al, 2002, p.1; Gallopin et al., 2001). In addition, physical and non-physical flows and social interactions are increasingly interconnected and interdependent cascading across different levels and scales (Cash et al., 2006; Young et al., 2006). The regenerative capacity of nature's sources and the assimilative capacity of nature's sinks have not kept pace with the growth of population and the volume of consumption. Whereas at the turn of the 20th century, the limiting factors in the economy were labour and built capital, these are now abundant, but natural capital, including both sinks and flows, is scarce (Daly, 2005). Nevertheless, larger risks loom ahead if we refuse to grasp the complexity of the situation and to implement systemic change, instead of pursuing each problem independently.

Since the Enlightenment, the prevailing scientific paradigm has implicitly assumed that the problems are precise and can be reduced to their components to identify isolated and linear chains of cause and effect (Hjorth & Bagheri, 2006). While this thinking has generated scientific breakthroughs and innovations, it has decreased our capacity to face growing complexity and the inter-relatedness of environmental, social and technological systems. In response, an emerging approach based on the theory of complex adaptive systems treats sustainability issues and the Grand Challenges as 'wicked' (Rittel & Webber, 1973) and ill-defined (Scholz, 2011). Complexity and systems thinking entail replacing linear cause-and-effect logic with a search for explanations from circular causality (Waltner-Toews et al., 2008, p.3) and co-evolution (Rammel et al., 2007). Table 1 characterises[1] the differences between the traditional and the emerging complexity-based approaches to problem-solving and sustainability challenges. In recent years, the theory of complex adaptive systems has generated two particular approaches to sustainability change: social-ecological and socio-technical approaches,

[1] The characteristics are rendered on a very general level in order to highlight the very distinctiveness of the two lines of thinking. 'Linearity' of the traditional approach here, refers particularly to the logic of isolated and clearly visible cause-and-effect chains with assumption of ceteris-paribus functioning (Bunge, 1979; Hutchinson, 1948). Furthermore, a complexity-based approach is more like an umbrella accommodating a range of school of thoughts in the 'sustainability science' field.

which depart from different origins and backgrounds, thus demarcating and analysing the system in different, but for this thesis, complementary ways.

Table 1: The differences between traditional linear-based research approaches and emerging complexity-based ones[2]

Attribute	Traditional linear approach	Complexity-based approach
Default orientation	Stability (equilibrium) or incremental change	Dynamic stability (incremental change along the existing trajectories) and radical change
Causation	Single, separable and linear chains	Multiple, non-separable feedback loops
Uncertainty	Eliminate uncertainty	Incorporate uncertainty
Perspective on risk	Minimising short-term risk by optimisation	Preparing for long-term risk by diversification
Knowledge	Unknowns are reduced with simplifications	Knowledge is always incomplete
Type of problems	Discrete and clearly defined problems	Complex and ill-defined problems

1.1 Positioning of the thesis within the current research

1.1.1 Theoretical positioning of the thesis

This thesis is positioned within an interdisciplinary context, utilizing research concepts that have originated in natural and social science disciplines, but that employ systems thinking as a common denominator. These research strands, namely ecosystem management, global environmental change, and resilience from the natural sciences; and evolutionary economics and innovation and technological change from the social sciences, form the essential background for the two distinctive approaches applied in the thesis. The social-ecological and socio-technical transition approaches are applied to sustainability change in the context of the food system, which cuts across the disciplines; see Figure 1. In addition, sustainability science is influential in bringing in

[2] Adopted from Gallopin et al., (2001).

the different modes of doing research, implying that it is not only analytic and descriptive, but also solution-oriented, normative and transformative[3].

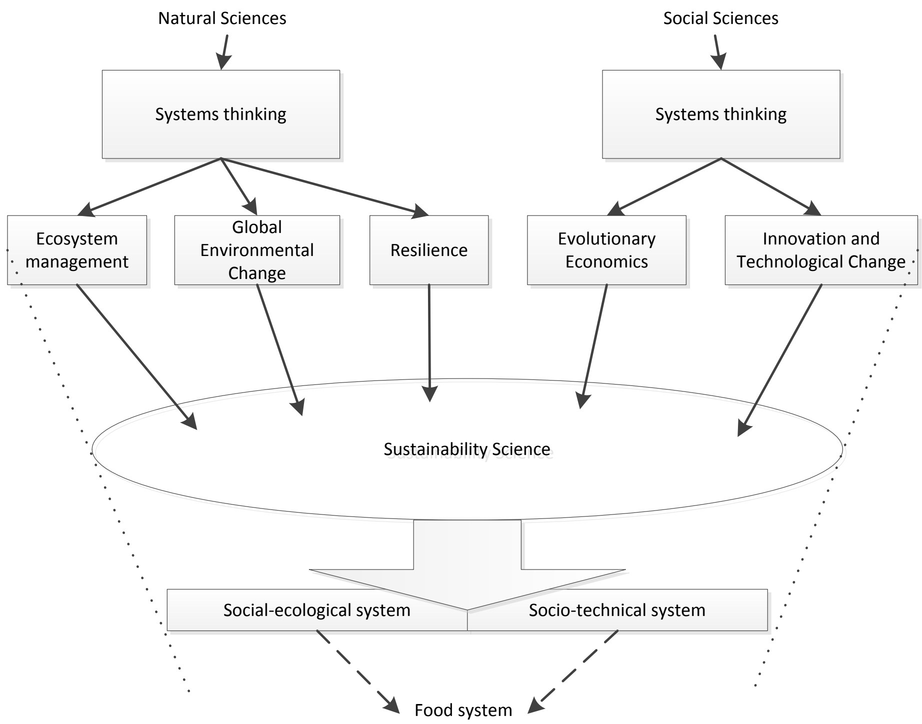

Figure 1: Theoretical positioning of the thesis

Sustainability science emerged in response to the growing number of complex and intertwined environmental and social-environmental problems (Lang et al., 2012; Clark & Dickson, 2003). Its rationale builds on three premises: 1) the complexity of sustainability problems requires constructive input from various communities of knowledge in order to ensure that all relevant actor groups are incorporated; 2) research on solutions requires an understanding of goals, norms and visions that guide transitions and intervention strategies; 3) collaboration between the academic and non-academic worlds creates opportunities for higher legitimacy, ownership, and accountability of the problem as well as solution options (Kates et al., 2001). Thus, it explicitly aims to contribute to the sustainability transformations, and hence it is agenda-driven. It aims to bridge the natural and social sciences for inter- and multi-disciplinary understanding of the problems involved (Jerneck et al., 2011). In addition, a transformational mode of

[3] Sustainability science is not only interdisciplinary but also trans-disciplinary, which refers to mutual problem framing and learning between science and non-science practice community (also referred to as co-design or co-production) (Scholz & Steiner, 2015).

research relies on different types of knowledge, including normative, anticipatory and action-oriented knowledge, which can be considered uncommon in comparison to more traditional science, which builds solely on descriptive and analytical data of the past or the present (Wiek et al., 2012), thus often differing in ontology, epistemology, methodology, functionality and organisation (Scholz & Steiner, 2015). However, while the thesis is 'for' sustainability change, in fact, none of the papers is truly based on engagement in multi-stakeholder action for system transition.

Social-ecological system approach

Environmental sustainability was long perceived as the management of the availability of scarce natural resources and pollution. The introduction of a range of services ecosystems maintain: i.e. provisionary, regulatory, supporting and cultural services (TEEB, 2016), expanded the prevailing scope and focus, giving emphasis to environmental integrity (Grumbine, 1994). In addition, an ecosystem-based approach highlights how the services are generated by the interaction of various cycles and subsystems, e.g. the global biosphere. The first large-scale global assessment of ecosystem services, the Millennium Ecosystem Assessment (2005), highlighted the vital role of ecosystem services in human well-being, essentially connecting the environmental system to the social one, which had traditionally been viewed as separate entities. Thus, the ecosystem service approach extended the view in which for instance well-functioning nutrient cycling, in addition to the cycling of other key elements such as carbon, freshwater, sulphur and others, is the backbone of the life-supporting biosphere, with people being embedded in it (Folke et al., 2011). Hence, not only the resources but also the ecosystem's capacity to sustain itself and the flow of resources requires stewardship.

Global environmental change research originated in studies of climate change and local environmental management practices. Although by now it has expanded to an analysis of cross-scale interaction from global to local, focusing on other human-induced environmental changes, such as biodiversity loss, land change and freshwater scarcity. Global environmental change research emphasises the human dimension in both the undesirable geo-biochemical changes and the desired transformations. Particularly, the concepts of resilience, vulnerability and adaptation have become influential in understanding human dimensions of global environmental change (Ostrom & Janssen, 2006). Originating in the natural sciences, the global environmental change research community is urged to cross the scientific boundaries of the natural sciences towards conducting research involving the full range of sciences and humanities, to better address sustainable development and the 'grand challenges' (Reid et al., 2010).

Resilience that originated in mathematics and ecology (Janssen et al., 2006) became particularly influential in other fields beyond ecology, at least in the fields of social learning, sustainability science, risk and vulnerability in human-nature systems, systems science and sustainability, thus becoming a game-changing concept (Folke, 2006). Rather than trying to manage and control the ecosystem as a state of equilibrium, Holling (1973) argued that environmental changes are non-linear, and hence it is more critical to maintain a system's capacity to accommodate disturbance and shocks, i.e. the resilience of the system. This resilience approach embraces the view of inherently intertwined social and environmental systems. The definition of resilience has evolved from a narrower understanding of persistence and buffer capacity to encompass adaptive capacity and transformability, and it is often also defined as the capacity to absorb disturbance and to reorganise while retaining essentially the same function, structure, identity and feedbacks (Folke et al., 2010). A key insight generated from resilience is a focus on uncertainty and incorporation of change as a normal system state rather than a focus on stability and equilibrium, thereby emphasising the proactive role of individuals, communities and institutions in managing by change (Folke, 2006). Another contribution has been the idea of critical thresholds or tipping points[4], beyond which the system, as broad as the Earth system, can decay into an unpredictable and irreversible state (Biermann et al., 2012), thus stressing a precautionary view in regards to global environmental change. In this respect, the identification and quantification of planetary boundaries has become the first attempt to operationalize Earth-scale resilience, i.e. the safe operating space for humanity (Rockström et al., 2009).

Socio-technical transition approach

Similarly, at the societal level sustainability problems were initially linked to merely point-source pollution or scarcity of non-renewable resources. Such discrete problems were easily tackled with technical improvements and innovation. However, the enlarged scope of environmental problems broadened the scale of the needed solutions. From end-of-pipe technical fixes, the focus expanded to system innovations, constituted by radical shifts in system components and disruption of existing system linkages (Elzen et al., 2004). Such system innovations, i.e. shifts from one socio-technical regime to another, are grounded in the idea of co-evolutionary processes between technology and social structures and practices (Geels, 2005). The co-evolutionary perspective 1) explained how the past technological development could actually be the cause of the current sustainability problems (van den Bergh & Gowdy, 2000), and 2) provided a more comprehensive view on how system innovations come about through multi-level interaction between different hierarchical rule structures, in which actors and their practices are embedded (Geels, 2005). It implies that technological innovation does not emerge in a vacuum but instead comprises changes in user practices and institutional structures, in addition to technologies and artefacts (Markard et al., 2012). Hence, socio-technical transitions have been used as an analytic framework for the past transitions, and as a normative, guiding approach in the governance of sustainability change, in addition to broadening the scope of innovation activity per se (Smith et al., 2010).

Research interest in innovation and technological change has been especially driven by the rationale of economics, which links innovation performance to economic growth.

[4] Approaching tipping points refers to approaching system state, in which probability of non-linear, unpredictable and irreversible regime shifts increases.

Hence, innovation research has a strong tradition of informing policy on drivers and barriers to innovation within organisations, sectors and regions. This line of inquiry originates from the notion of market failures that explain and justify why even perfect competition does not always lead to an optimal allocation of resources (Smith, 2000; Arrow, 1962), hence legitimizing policy intervention. For instance, due to invisibilities, inappropriateness and uncertainty of knowledge creation, basic research is often underinvested in, and research and development is underfunded. Other typical failure arguments particularly relevant to environmental issues refer to the problem of externalities and over-exploitation of common goods, which, in the absence of property rights, can be easily exploited to a higher degree than what is viable.

1.1.2 Empirical positioning of the thesis

Empirically speaking, this thesis focuses on the food system on various geographical and analytical scales. Research developments in food security, food policy and food system studies are particularly relevant in this respect as they cut across the fields of natural and social sciences. Food security expanded from being merely supply and quantity-oriented to addressing more systemic issues, such as access to assets that can be converted into food, and equality of allocation and distribution (Sen, 1981). Particularly the most recent food price crisis in 2008-09 renewed the concerns of food security not only in developing but also increasingly in industrialised and emerging countries alike (Ingram, 2011). Not surprisingly, food security is considered as the central goal connected and connecting to all other Sustainable Development Goals (Rockström & Sukhdev, 2016).

According to the narrow, quantity-oriented food security view, food systems were conceived as a supply chain of activities from production to consumption. The chain-view particularly emphasised value-adding activities, but excluded the various socio-economic structures that constrain and enable these activities, as well as the interaction between social and environmental components, which is still essential to any agricultural production. As the view hitherto focused mostly on supply side activities, it was largely based on agronomy (Ingram, 2011). Thus, broadening the analytical scope to include systems enabled a more nuanced understanding of the complex issues at play, incorporating multi-level interaction between social and environmental systems, as well as including both the food system activities and their outcomes (Ericksen, 2008).

The thesis follows Ericksen's (2008) food system conceptualisation, for it spans and reflects more than one analytical scale and traces cross-scale and cross-level interactions, making the focus of social-ecological and socio-technical approaches complimentary; see Figure 2. The social-ecological approach addresses the environmental feedback loops between biochemical phosphorus and nitrogen cycles and the food system outcome, namely global food security. The socio-technical approach addresses the socio-technical feedback loops between the socio-technical regime dynamics and food system activities and practices. Furthermore, both approaches have several scales and levels, described in more detail in Table 2. However, it is worth mentioning that the social-ecological approach deals with geographically spatial scales, from global to local, whereas the socio-technical approach deals with rule- and power-based hierarchies, from low to high levels of coerciveness and influence.

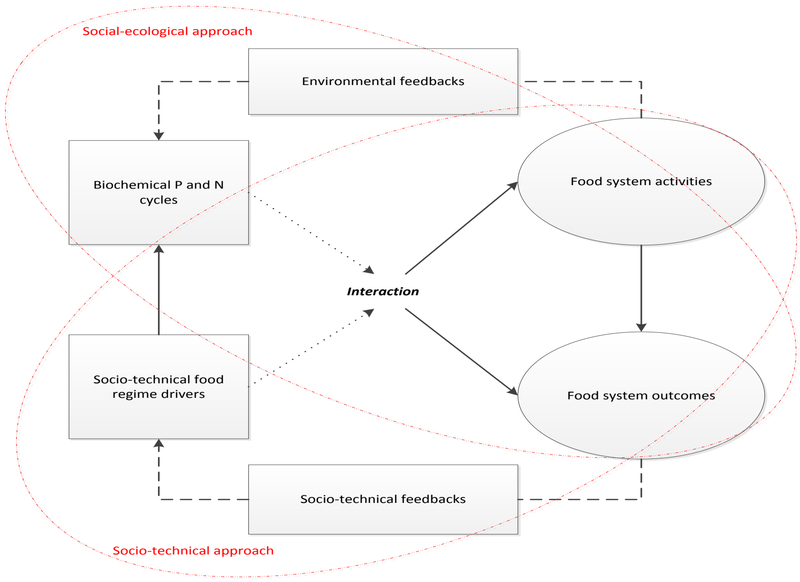

Figure 2: Food system conceptualisation in the thesis (adapted from Ericksen (2008))

Table 2: The scales and levels of the thesis

Scales/Levels	**Geographical**	**System boundaries**	**Analysis**
Paper I	Global	Social-ecological	Descriptive and anticipatory

Paper II	Global and local	Social-ecological	Analytic
Paper III	National	Socio-technical	Exploratory and descriptive
Paper IV	National	Socio-technical	Exploratory and normative

1.1.3 Sustainability and resilience

Although a deep analysis of sustainability and resilience is outside the scope of this thesis, it is worth outlining the main differences in the use of the two concepts. Firstly, as Redman (2014) notes in his analysis of the two concepts, some scholars merge the two intentionally in the pursuit of a combined approach. Particularly, as resilience thinking is applied in various practical fields such as urban resilience, disaster resilience or community resilience (Davidson et al., 2016), and has broadened from merely ecological to social-ecological systems and their transformations, the concept of resilience has become more ambiguous, subjective and normative (Adger et al., 2005; Brown, 2013). This brings it closer to the sustainability transition domain (Smith & Stirling, 2010). Here, sustainability and resilience are understood as closely related, yet neither synonymous nor interchangeable. Firstly, sustainability is inherently perceived as 'strong' sustainability[5] that cannot be achieved without resilience, yet environmental resilience does not necessarily imply sustainable outcomes for social world, for there can be various resilient system states, but not all of them socially feasible (Hodbod & Eakin, 2015). There is no aspiration to integrate or unify them, but rather to use the strengths of each in their original context: resilience in the analysis of the social-ecological system and sustainability in the analysis of socio-technical (or societal) transitions of sustainability change in general. While resilience highlights the intrinsic value of environmental functions, sustainability is necessarily a normative concept and open to interpretation and negotiation. Hence, socio-technical transitions are messy by default and include a competing and even conflicting agency of participating actors. Sustainability is an objective of or a desired direction of change in the societal systems, while resilience is a measure for dynamic and non-linear behaviour of social-ecological systems. The main strengths are that sustainability approach systematically integrates normative values and anticipatory thinking into future- and transition-oriented strategies, while the resilience approach focuses on system dynamics that can improve

[5] Strong sustainability implies non-substitutability between natural and manmade capital (Daly, 1991), and the three pillars of sustainability dimensions in general. Strong sustainability is also in line with a functional ecosystem-based approach that appreciates environmental integrity (Ayres et al., 2001).

adaptability in the face of inevitable, yet unspecified, external shocks and stressors (Redman, 2014). Broadly speaking, the resilience approach does not require the prediction of outcomes, but instead aims to prepare for unknown futures, whereas the sustainability approach aims at identifying desirable futures and pathways to reach the desirable futures amid sometimes conflicting values and priorities (*ibid.*).

1.2 Research gap

There are two profound theoretical approaches to systemic change: social-ecological and socio-technical approaches. Although both focus on systems, they demarcate the systems differently and hence highlight distinct issues in terms of sustainability change. Both approaches leave a research gap that can be filled by the other one. The social-ecological approach demarcates the system as a co-evolution between social and environmental systems in a particular geographical area or on a global scale. The socio-technical approach focuses on the co-evolution of technology, institutions and practices at the societal level, and is not necessarily bound to a spatial scale, but rather to the hierarchy of rule structure. Furthermore, in addition to the theoretical research gap, systemic sustainability approaches taking explicit account of environmental and societal system functioning, have heretofore been scarce in the context of food systems.

While it has recently been argued that resilience and transformability are not contradictory when perceived as cross-scale interaction (Folke et al., 2010), it remains unclear resilience of which system or at which scale is desirable and consequently, transformation of which system or at which scale, is the prerequisite, highlighting the criticality of cross-scale dynamics. Particularly as the food system sets additional restrictions, the aim of resilience should be included in defining the state in which food security on all scales for all is possible, and in providing insights into how to maintain the system in this resilient state (Hodbod & Eakin, 2015). Planetary boundaries, as defined by Rockström et al. (2009), are useful, yet deserve more scrutiny and inclusion of spatial differences. In particularly, as they are defined on a global scale, they do not address regional distribution of impacts or historical patterns, thus dismissing accounts for equity and causation (Steffen et al., 2015).

Socio-technical research is interested in the interaction among different societal levels, niches, regimes and landscapes that are defined by the coerciveness of rule structures. The essence of change is that a regime is by nature stable and conservative, due to its path-dependent nature. Therefore, the needed radical change requires multi-level interplay, in which the pressure faced by the regime can create opportunities for niches and restructuration processes. The main gap in the approach is its lack of taking the environmental system into explicit account. In other words, system transition is analysed as a process, but the quality and the direction of change is not subject to scrutiny. In addition, it is important to consider the history of the current regime, as it can reveal why it operates the way it does, and why achieving a higher level of sustainability is difficult. Furthermore, so far, sustainability transitions have only been loosely connected to the policy level, particularly to the innovation policy level. Nevertheless, policy level is an essential part of system innovation and can be the source of hindrance to the sustainability transition.

In addition to theoretical research gaps, understanding of sustainability change in the context of food systems has thus far been sparse, for several reasons. Firstly, the scale of the sustainability change needed has not been defined explicitly, particularly considering a functional ecosystem-based approach to the nutrient cycling of nitrogen and phosphorus and the view of the entire food system, from production to consumption. In this respect, the social-ecological approach departs explicitly from the environmental perspective, determining the boundaries within which the system is resilient and thus can maintain sustainability in the long term. Secondly, sustainability change has lacked attention placed on the food system's socio-technical structures and practices that not only enable but also constrain the desired change, particularly in terms of a more sustainable nutrient economy. The socio-technical approach focuses explicitly on these issues and aims to identify the mechanisms hampering transition at different levels. Thirdly, the cycling of nutrients, namely nitrogen and phosphorus, despite being instrumental to the sustainable food systems, is usually treated either merely as managing inputs in agriculture or as managing pollutants in the waste management sector. Thus, herein a distinction is made by using a broader concept, namely that of the nutrient economy, which, in addition to physical nutrient flows, consists of non-physical institutions and practices that regulate the flows. As such, the sustainability of the nutrient economy underlies the food system and its transition. Finally, system innovation addressing the nutrient economy has lacked policy-level analysis in regards to stimulating system innovation.

1.3 Aims and objectives

In this dissertation, the aim is to approach the food system as a complex adaptive system and thus to understand the challenge of sustainability change in the food system. The sustainability focus is particularly on the flows of two main macronutrients, phosphorus (P) and nitrogen (N), which support and enable the production of food. As such, sustainability does not only address agricultural inputs and their use, but also the sustainable functioning of nutrient economy, which connects the biophysical system to the social one. Just as social systems depend on the exploitation of natural resources and the assimilative capacity of the environment, they impact on environmental systems, giving rise to negative and positive feedback loops and co-evolution between the two systems. At the scale of Earth system, nutrient cycling represents one of the interlinked environmental systems that set the thresholds for safe operating space for human systems to develop and evolve (Rockström et al., 2009). Thus, *the first research question investigates the planetary thresholds of nitrogen and phosphorus within which food systems should evolve in order to maintain within the sustainable scale providing global food security to all.*

Planetary boundaries (Rockström et al., 2009), addressing the integrity of environmental system functioning, are defined on a global scale for the aggregate human impact, thus leaving many issues, including cross-scale spatial and temporal dynamics unspecified. Nevertheless, due to systemic properties of social-ecological systems, such as cascade or delay of feedback loops, different local environmental conditions and historical patterns of nutrient use can have different impacts on the thresholds as well as on the gap to be bridged. *The second research question aims to approach the critical thresholds in a bottom-up manner, comparing local to global thresholds, and in a temporal scale, addressing the historically cumulated use of nutrients in different regional contexts, thus addressing the social perspective of planetary boundaries.*

The socio-technical regime fulfils societal needs such as food in a particular way; it is a complex combination of incumbent technological, political, socio-cultural, scientific and regulatory structures that mediate actors' practices and has co-evolved over a long period of time. The systemic property of path-dependency of co-evolutionary processes can lead to regime's lock-in creating systemic resistance to sustainability change. Moreover, unawareness of the lock-in can reinforce the unsustainability of the food system and be the problem as such. Therefore, *the third research question aims to identify the path-dependent mechanisms in the food system in order to understand their origins and their dynamics in stimulating the system lock-in.*

System innovation, through re-shuffling the entire architecture of both the production and consumption systems, is propagated to solve the sustainability issues. Innovation studies prominently analyse the barriers for innovation diffusion, but they mostly focus on failures within a single organisation or in regards to a clearly demarcated innovation. The failures faced by system innovation are much more complex and wide-ranging. In addition, although innovation studies are well established at policy level through the lens of the concept of failures, system innovation is only loosely connected to policy level. *Therefore, the fourth research question investigates into the failures that inhibit system innovation, thus connecting sustainability transitions to the policy level.*

Figure 3 outlines the research aim and approach. A systemic perspective is applied in two analytical ways: 1) a social-ecological approach is applied in order to identify the scale of the needed sustainability change when applied to the food system, while 2) a socio-technical approach is applied to analyse the feedback loops causing and amplifying the unsustainability through path-dependent mechanisms. Then, a normative approach is taken in identifying failures inhibiting sustainability transition, in other words system innovation. Thus, the thesis poses the following questions:

1. What does a planetary boundaries approach imply for the food system, when it is complemented with the inclusion of fossil-fuel combustion, biological nitrogen fixation and the known availability of phosphorus reserves? What is the magnitude of the needed transformation in order to return to the safe operating space?
2. What does a local bottom-up and temporal assessment of planetary boundaries varying in space entail for the food system?
3. How and what are the mechanisms that have created and maintained an unsustainable food regime resisting its change?
4. What are the failures inhibiting system innovation in the food system?

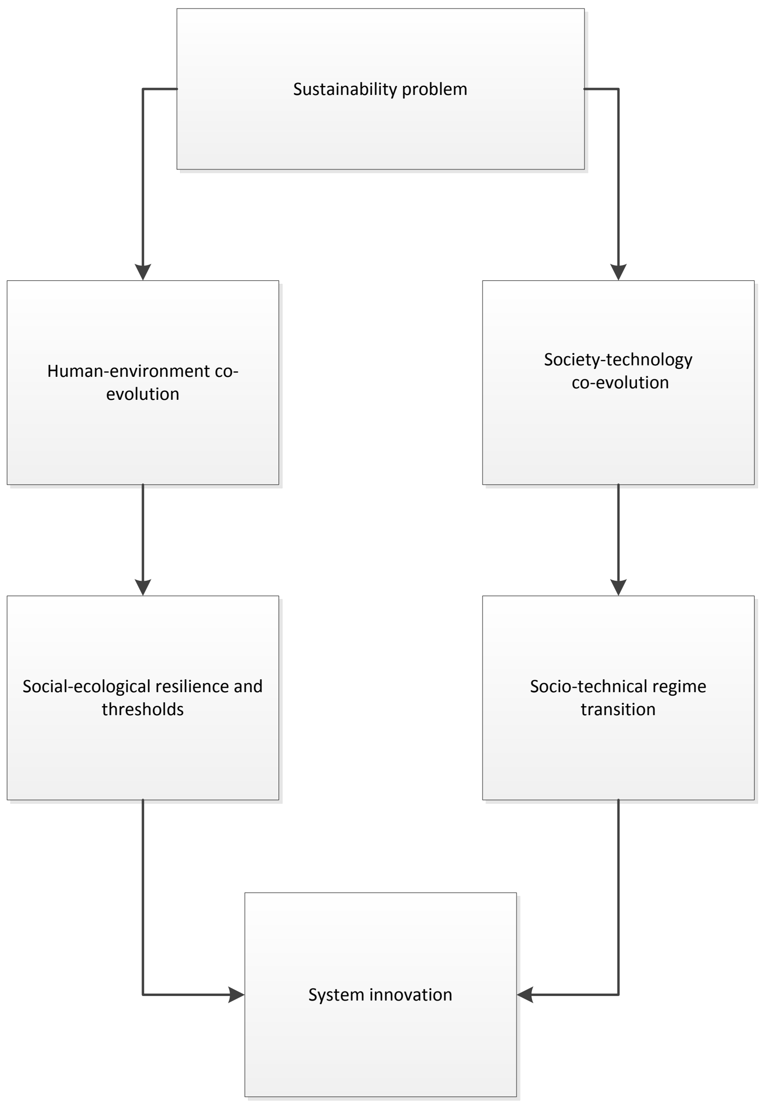

Figure 3: Research approach framework

1.4 Structure of the thesis

This dissertation incorporates the summary part of the thesis and four publications. This summary part is structured hereafter as follows. The second chapter outlines the theoretical framework in which the research questions are grounded. The third chapter presents food system in relation to the growing unsustainability gap of nutrient economy. The fourth chapter discusses materials and methods, while the fifth chapter presents the results. The sixth chapter discusses the implications of the results and makes concluding remarks.

2 Theoretical framework

Already in the early 1970s, Rittel and Webber (1973) pointed out that modern science is better prepared to deal with 'tame' problems than with wicked ones, and that in today's pluralistic societies, responses cannot be meaningfully correct or false, and least of all optimal. Wicked problems have some distinguishing properties that render traditional and classic approaches useless. They have no definitive problem formulation, yet formulation itself is a problem; there is no immediate or ultimate test of a solution and every attempt at the solution is consequential; thus, every wicked problem can be a symptom of another problem (Rittel & Webber, 1973). In response, cybernetics, system dynamics and general system theory, evolving from the late 1940s onwards, contributed to better understanding of complexity and complex system dynamics (Scholz 2011, page 355). In an attempt to find generalisable dynamics and principles of open systems, be it in biology or human behaviour, general system theory was concerned with wholeness and the problem of organised complexity (von Bertanlaffy, 1968). This implies that systems are seen as embedded in a conceptual grid, while system's subsystems are inextricably coupled and hence cannot be seen independently of the system or each other (Scholz & Tietje, 2002). The theory on system dynamics introduced feedback loops with properties of delays, accumulation and non-linearity (Sterman, 2001). Every living and natural system is by its very nature and definition an open system maintained through a constant exchange with its environment, so environmental, technological and socio-economic systems all can be understood as complex adaptive systems (CASs) characterised by general properties of self-organisation and co-evolutionary dynamics (Rammel et al., 2007). These properties provide insights and tools for analysing and managing sustainability change.

CASs are comprised of nested hierarchies that are self-organising and emergent, implying that large macroscopic patterns emerge out of local, small-scale interactions among system components (or agents) themselves as well as among system components and their environment (Rammel et al., 2007). Self-organisation means that the system is more than 'the sum of its parts' and has an 'identity' of its own (Waltner-Toews et al., 2008, p.4). This is contrary to reductionist science, which aims to break the system down into components and to examine each component in isolation from all the other components, thus neglecting the interaction of components that gives rise to positive and negative feedback loops (Berkes et al., 2002). Furthermore, the strong coupling between the different hierarchical levels implies that systems must be analysed and managed at more than one scale simultaneously, but since interaction and system characteristics differ, it is impossible to have a unique, correct, and all-encompassing perspective (Gallopin et al., 2001). Understanding that a given system's hierarchical levels and relationships are internally structured and develop over time has implications for a number of surprising and counterintuitive phenomena (such as path dependency) that arise from this property (Waltner-Toews et al., 2008).

Complex adaptive systems are co-evolutionary systems, meaning that they co-evolve through a dynamic interaction with other interdependent systems and their environment. Particularly for sustainability, it has been important to identify the following co-evolutionary dependencies:

- Technology and society (Winter & Nelson, 1982; Nelson & Winter, 1977; Rip & Kemp, 1998)
- Technology and industrial structures (Dosi, 1982)
- Technology and institutions (Foxon & Pearson, 2008; Nelson, 1994)
- Social and ecological systems (Folke, 2006; Holling, 1973; Norgaard, 1984)
- Environment and institutions (Rammel et al., 2007; Hjorth & Bagheri, 2006)
- Technology and environment (Berkhout, 2002)
- Institutions and individuals' behaviour (Rammel et al., 2007; van den Bergh & Stagl, 2003).

CASs change through evolutionary processes, signifying that previous events and steps matter for further steps. The main evolutionary processes are selection and variation, which give rise to the new system state. However, neither selection nor variation exists independently of related context or history. Concerning technological change, Dosi (1982) noted that technological and scientific paradigms pre-define the patterns of emerging technologies and direct the innovative process towards a particular direction. Since a CAS evolves out of its selective context, it can be perceived as part of a causal chain of undetermined evolutionary development, which is path dependent (Rammel & van den Bergh, 2003). Path dependency is thus characteristic of evolutionary systems and merits a more in-depth analysis in section 2.3.

The concepts of self-organisation, emergence and co-evolution improve understanding of the nature of change in complex adaptive systems. The nonlinearity of CASs implies that change inherently contains high levels of uncertainty, making it non-predictable. Because of this non-predictability, it does not follow that change is entirely random; certain outcomes can be more probable than others, but it is impossible to predict, and also to manage, the outcome ex ante. Non-linearity of CASs also signifies that there is no single equilibrium or stable state; instead, there are several possible equilibriums (Berkes et al., 2002, p.5). Plurality and uncertainty are thus inbuilt and cannot be reduced entirely.

Another common characteristic of CASs is adaptation through change. Since there can be several equilibriums, CASs must be able to adapt to different equilibriums, making optimisation efforts local and myopic (Rammel & van den Bergh, 2003). In evolutionary thinking the aim is not necessarily stability in a static sense, but rather high levels of adaptive capacity, which increases the resilience of the system in the long term. Resilience helps the system to withstand external shocks and maintain its main structures within the same basin of attraction up to a certain extent (Berkes et al., 2002; Holling, 1973; Young et al., 2006). Thus, one of the essential elements of adaptive capacity is maintenance of diversity for long-term stability (Rammel & van den Bergh, 2003; Low et al., 2003). Another crucial element is the necessity of learning, especially learning-by-doing and collective learning of organisations and institutions (Berkes et al., 2002). Resilience can thus be perceived as maintaining a long-term systemic efficiency based on functional diversity, as opposed to the standard economic understanding of efficiency that tends to decrease functional diversity for the sake of short-term, narrow efficiency (Rammel & van den Bergh, 2003; Stirling, 2007).

As complex systems thinking propagates the vague idea that everything affects everything, it deserves the critique that researchers cannot grasp everything at once. Even in applying systems thinking, the researcher must take decisions on system boundaries, what to include and exclude; which links are meaningful and which ones obsolete. These decisions are necessarily subjective and reflect the viewpoint and the understanding of the analyst, making it impossible for any scientist to claim to be an objective observer (Waltner-Toews et al., 2008, p.10). In addition, complexity based approaches may involve more than one unit, or object of analysis, and may apply multiple evidence and research methods for investigating different subunits of the case (Scholz and Tietje, 2002, 9-10), depending on researchers' competence and proficiency of following different epistemic line of analysis (Scholz and Tietje, 2002, 334). However, this is one of the crucial differences to the reductionist approach. In systems thinking, the impossibility of grasping the wholeness of complexity and hence the high level of uncertainty and unpredictability is intrinsically acknowledged. Thus, the aim of scientists is not to find the one correct answer, but to evoke untraditional questions and provide a broad range of answers.

2.1 Social-ecological approach

Social-ecological research emerged from the natural sciences, abandoning the view that ecosystem changes are linear, predictable and controllable, and providing a new view of tightly coupled social and environmental systems (Folke et al., 2005). Its central tenets revolve around resilience and transformation in human-environmental interactions and feedbacks in order to reverse the currently unsustainable trends, such as loss of biodiversity, climate change and biophysical nutrient cycling (Westley et al., 2011; Folke et al., 2011; Olsson & Galaz, 2012; Steffen et al., 2011). Introduction of resilience shifted the predominant view in ecosystem management that emphasised stability and 'equilibrium' to internalising expectations of disturbance, variability and change (Holling, 1973). Originally, Holling (1973) defined resilience as the time a system takes to return back to equilibrium when disturbed, thus emphasising the system's persistence. System's resilience implies the buffer from external influence maintaining the basic nature and functioning in the face of disturbance (Berkes et al., 2002). To exemplify, the greater society's resilience is in confronting externally imposed change, the greater its ability to absorb external shocks and perturbations, and vice versa (Adger et al., 2005). However, when the impact grows beyond certain tipping points (also, thresholds), a small change can cause the system to alter dramatically, without giving any warning signals in advance (Waltner-Toews et al., 2008, p.6). Since such change is mostly uncertain and its impacts are unpredictable, sustainability of a social-ecological system depends upon maintenance of the adaptive capacity to support social, economic and environmental systems (Berkes et al., 2002, p.2). Hence, more recently, the resilience approach has emphasised an adaptation to shocks by change (Carpenter et al., 2001); thus, an active and deliberate transformation on lower scales maintains resilience on a higher scale (Folke et al., 2010). The Resilience Alliance defines this along three dimensions (Carpenter et al., 2001):

I. The amount of perturbations the system can absorb and withstand, and still retain the same controls on function and structure, or still remain within the same domain of attraction;
II. The degree to which the system is capable of self-organisation; and
III. The ability to build and increase the capacity for learning and adaptation.

2.2 The social-ecological food system

Resilience of the socio-ecological food system is governed by the interaction of global environmental and social changes and by the consequent environmental and socio-economic feedbacks generated by food system activities and outcomes, cf. Figure 2 (Ericksen, 2008). Social-ecological approach emphasises the uncertainty instead of stability as the norm, in which change can be both gradual and slow, such as slower internal drivers (soil nutrient depletion, or shifts in consumer values), or fast and unforeseen, such as price spike or disease outbreak (Hodbod & Eakin, 2015). Shocks may be transmitted over long or short distances and via few or many processes, but increasing the amount of cross-scale interactions makes governance of shocks particularly difficult and uncertain (Young et al., 2006). As resilience declines, the food system moves closer to the thresholds, implying that smaller disturbances can have a larger effect, triggering reorganisation and renewal within a system or system (as we know it) collapse and moving to another regime state (Folke, 2006). The social-ecological food system has only one regime state to achieve, or in which to maintain the resilience (Hodbod & Eakin, 2015): the food system must be in a state of maintaining adequate food security for all humans at all times.

The study of planetary boundaries (Rockström et al., 2009) was the first in trying to identify and quantitatively define the critical thresholds of interlinked environmental processes at global scale, taking resilience-oriented view on ecosystem functioning. Despite the criticism towards quantifying global scale tipping points (Schlesinger, 2009;

Brook et al., 2013; Lenton & Williams, 2013), the lack of social dimension (Scmidt, 2013), and the choice of specific boundary (Carpenter & Bennett, 2011), planetary boundaries approach is an important step in operationalizing the 'limits to growth' thinking (Kahiluoto et al., 2014) and precautionary principle towards inducing global environmental change (Brown, 2015). Furthermore, it emphasises the functional view on ecosystems and its interaction with human needs and activities. Nevertheless, planetary boundaries should be viewed as the first guess, and stimulate more scrutiny and elaboration.

2.3 Socio-technical approach

Socio-technical research emerged from innovation, science and technology, sociology and systems thinking, out of the realisation that technological change was not driven merely by individual technology or an engineer but also by the social construct in which the technology and engineering process is embedded. A broadly cited multi-level perspective has become prevalent in illustrating societal system change in various regimes, such as those of energy, mobility and agriculture sectors, to name a few (Geels, 2004; Geels, 2002). A multi-level perspective distinguishes between three hierarchical levels of power constellations: landscape, regime, and niche, through an interplay of which a shift from one stable state to another one takes place (ibid.). The three levels are nested within each other: the regimes are embedded in landscapes and niches within the regimes (Geels, 2004, p.36). In addition, different levels represent different strengths of structuration of local activities and rules. In the case of niches, the connections and coordination forces are loose; hence, the activities of niche-actors can go in different directions. In the case of regimes, rules are stable and have a coordinating and guiding effect on the activities of actors. Landscapes provide an even stronger structuration, as they form gradients for action, and actors cannot really influence landscape factors (Geels, 2004, p.36). The meso-level regime superimposes a particular logic and direction on scientific knowledge, engineering practices, technological improvements and user expectations. The logic can be understood as the 'rules of the game' or more formally be connoted as institutions that coordinate and constrain actors' practices within the regime (Geels, 2004). Although not deterministic, rules bind and guide the actors who actively use, interpret and reform them through everyday practices. The regime is a constellation or alignment of other regimes, such as science, policy, technological, socio-cultural, user and market ones, which share their own specific rule-sets that formulate the norm for the actors of that regime, and which provide the deep structure of the socio-technical system (STS) (Geels, 2004). Although niches operate at least partly outside the regime, the regime imposes selection forces that choose the winning technologies and innovations. Therefore, new technologies do not emerge or exist in a vacuum, while agency of actors arises through structuration processes in the regime.

Regime represents the mainstream of system structure and functioning, i.e. it is descriptive of how a particular societal need is fulfilled. Regime tends to be conservative, for it stabilises and reinforces the status quo around the equilibrium with reinforcing mechanisms such as path dependence and lock-in (Unruh, 2000; Arthur, 1994; Arthur, 1989; Foray, 1997). Stabilising mechanisms occur along the following three dimensions: 1) rules become aligned to a particular configuration; 2) actors and organisations become embedded in an interdependent networks and mutual dependencies; and 3) hard infrastructure creates complementarities, sub-components, and increasing returns, draws investments and adapts users to particular preferences (Geels, 2004). Due to the predominantly stabilising forces, a regime gives rise to incremental innovation along an existing path or trajectory, reinforcing the prevailing paradigm (Dosi, 1982), while more radical innovations emerge from niches (Geels, 2004).

The niche level is more turbulent and diverse since ties and network configurations are less formulated. The more a niche deviates from the regime's rule-set, the more radical it is (Geels, 2004), and the more difficult it can be to break through and replace the existing regime. However, as the rules and networks become more aligned and fortified, a niche can put pressure on the regime from the bottom up and contribute to creating momentum for an eventual breakthrough. Both a regime and niche are embedded in a socio-technical landscape, a macro level of slowly changing external factors, such as population growth, globalisation or temporary financial shocks, providing gradients for the trajectories (Geels, 2002). However, a regime constantly faces pressure, stress and tension from different levels, from above, from below and even from within if there are internal misalignments (de Haan & Rotmans, 2011; Smith et al., 2005). Ultimately, it is a combination of mismatch triggered by internal or external forces and a novel way of fulfilling the same need with a niche that can push the transition into a new regime (see Figure 4).

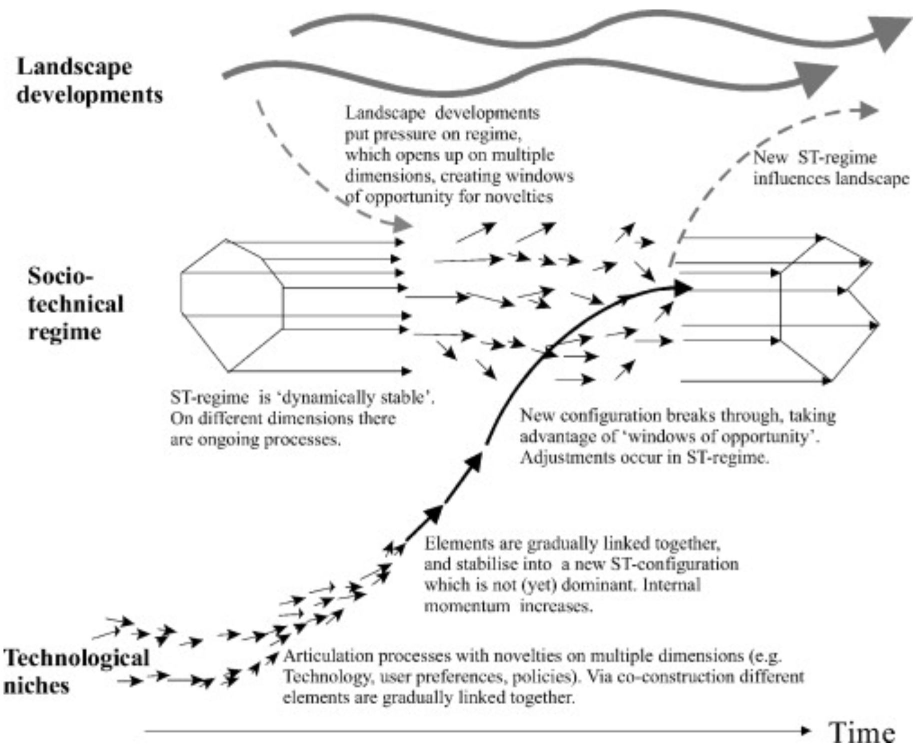

Figure 4: A dynamic multi-level perspective on system transitions[6]

The contribution of the multi-level perspective on socio-technical transition lies specifically in the multi-scale interaction, alignment, realignment and misalignment among heterogeneous elements in STS that form the basis for the regime shift. In addition, it emphasises the dynamics among different modes of system change, gradual and incremental renewal, and structural and disrupt system shift. Concerning the sustainability challenge, this perspective, combined with many others (such as evolutionary theory, actor network theory, reflexive governance and eco-innovation to name a few) (Markard et al., 2012), opened up new avenues for research and development along two separate, yet not mutually exclusive lines:

- An *analytic approach* examining why unsustainable regimes are so persistent and hard to change and how regime destabilisation can take place; and
- A *normative approach* focusing on promoting and governing transition toward sustainability, i.e. system innovation.

[6] (Geels, 2004)

2.3.1 The socio-technical food system

The socio-technical food system is a constellation of primary production, industry, user behaviour (consumption), policy, science, markets (including stock markets), and technology regimes. Broadly socio-technical food system can be defined through interaction of food system activities with socio-technical drivers and feedback loops, cf. Figure 2 above. The current food regime is presented with multiple landscape pressures, such as growth of affluent population and their preferences towards animal-based diets, demand for biofuels, environmental challenges and consolidation of global agro-food chains. Simultaneously, these pressures have excited niches that challenge the incumbent paradigm, such as alternative food movements and innovations. These niche-alternatives include organic farming, local food, La Via Campesina (International Peasant's Movement), genetic food, technological innovations, processing innovations, and dumpster diving, which all tend to focus on a particular aspect of food system challenges, including 'food miles', climate change, use of chemicals, loss of sovereignty, ethics and biodiversity loss. Some of the initiatives are at global scale, while others are more local or regional scale and instead of addressing a single-issue aim to induce system transition. As an example, in 2010 at Baltic Sea Action Summit, Finnish Council of State made a commitment to turn Finland into a forerunner of nutrient recycling (Ministry of Agriculture and Forestry, 2011), incorporating the entire food system, which is mostly contrary to prior initiatives to mitigate eutrophication and dead zones in the Baltic Sea.

2.3.2 Path dependency and lock-in

Path dependency is an inherent mechanism in evolutionary system change, from a cell level to social groups, as it helps to maintain consistency (Westley et al., 2011; Scheffer & Westley, 2007; van der Brugge & van Raak, 2007). It stabilises a system and facilitates reproduction of its internal dynamics by nurturing a new equilibrium (van der Brugge & Rotmans, 2007). Because of vested interests and sunk costs, it becomes more beneficial to follow along the existing path than to switch to another one (Rotmans & Loorbach, 2009). Thus, path dependency implies that there is no ex-ante most 'fit' technology. Only through the sequence of choices, driven by chance and trivial circumstances, will one technology eventually triumph over another (Foray, 1997). This has at least the following implications that make sustainability change and its governance more complex: 1) an unsustainable regime can be internally resistant to change (Harich, 2010), or locked-in (Unruh, 2000); 2) destabilisation of the regime can be required for system innovation to break through; and 3) limiting and narrowing down options too early may create new inefficient path-dependencies. Therefore, the greatest challenge is not that science cannot determine what is harmful or unsustainable, but that science and society are not well equipped to break out of lock-in. The existence of system inertia towards change means that desirable change is neither a question of one or even multiple actors' simply switching technology, nor citizens' behaviour change alone, but rather something more wide-ranging and subtle.

2.3.3 (Sustainable) system innovation and failures

In the 1970s-80s, such environmental problems as acid rain and air pollution were perceived more narrowly and locally, resulting in that discrete technical improvements could be promoted as a solution. Later, a clean technology approach was expanded upon with innovation integral to the processes and products, reducing contamination, waste and material use along the life cycle, and at best leading to reduced costs and material savings (Smith et al., 2010). Today, incremental efficiency-oriented innovation is confronted and outgrown, due to e.g. rebound effect (Holm & Englund, 2009), with the absolute scale of human impact, which is induced by not only production but also consumption processes (Wiedmann et al., 2013). Hence, the scope and scale of the solution has broadened in two ways: 1) the framing of the problem has redefined the purpose and boundaries of the innovative activity itself, from the clean technology of the 1980s to the innovation of entire systems of production and consumption; and 2) the framing of the analysis has included a wider set of considerations that can explain the emergence and success of innovation, shifting from mere price signals to a variety of innovation systems perspectives (Smith et al., 2010). Hence, the premise of system innovation lies in structural changes of existing socio-technical systems and related user practices, e.g. a transportation system and commuting preferences; or new social contracts, i.e. social and institutional innovations.

Innovation theory is traditionally connected to the policy-level with arguments of market failures. However, market-failure approach is fairly narrow in the sense that it often mainly focuses on clearly defined innovation performance in one organisation or sector, and to a lesser extent on the content and direction of innovation, which is the exact interest of sustainable system innovation. Performance of the innovation is no longer judged solely by its economic potential, but also by its impact on societal change and environmental and social sustainability (Smith et al., 2010). Market failures also neglect the demand-side dynamics and broader structural aspects which give rise to the selection environment, consisting of prevailing policies, institutions, infrastructure and innovation users (Geels, 2010). Moreover, in evolutionary view rather than correcting the market close to perfectly competitive state and efficient resource allocation, markets should be judged by their openness to experiments and to structural changes by novelty creation from within (Bleda & del Rìo, 2013; Metclafe, 1994). Thus, market failures are complemented with the identification of structural system failures that take into account the interactive and non-linear nature of the innovation process (Woolthuis et al., 2005). Market and structural system failures are concerned with micro-failures and innovation performance in terms of quantity at the firm level, but not so much with the system functioning itself, which is the object of system innovation. In addition, sustainable innovation is concerned with the quality of innovation, i.e. how the innovation is contributing to sustainable development; hence, not all innovations can be considered desirable. Linear models of innovation, which assume that greater levels of generic support for R&D will automatically lead to sustainable innovation are misleading due to ignorance of systemic, dynamic, uncertain and non-linear processes involved in system innovation (Foxon & Pearson, 2008). To align the failure approach with sustainable system innovation (i.e. transition), Weber & Rohracher (2012) proposed another set of transformative failures, which can better inform innovation policy and strategic orientation towards transformative change of the entire system.

3 The food system

The current food systems, from global scales to local ones, may be presented in a matrix of systemic properties and functional food system levels, which helps one to understand the complexity of the challenges. This complexity is not due to complicated system components, but rather to interaction and feedback loops between co-evolving systems, system components and the system's contextual environment. The system properties of connectedness, speed, spatial stretching and diversity; as well as equality in resources (nutrients, land, water, energy), production, supply chain, consumption, and political economy provide a comprehensive framework for outlining the socio-economic dimensions of the current food systems, all of which in interplay with global environmental change, affects the sustainability of food systems and environmental resilience (Kuokkanen et al., 2015). For instance, the global market of agri-food products connects local agricultural production to the global scale, and changes in the global markets or political economy of trade influence local practices. Moreover, increasing food trade naturally incorporates the trade of resources, thus also incorporating access to and appropriation of productive capacity beyond national borders (Rulli et al., 2012). In addition, food systems are increasingly interlinked with other systems and sectors, such as energy systems (McMichael, 2009) and the global financial sector (Burch & Lawrence, 2009). This was particularly evident in the latest food price crisis in 2008-09[7]. Meanwhile, the consolidation of global agri-food businesses and related marketing, and western consumption patterns and preferences are reducing the diversity of production and consumption systems.

In Ericksen's (2008) food system conceptualisation, nutrient availability and cycling are positioned among others as global environmental change drivers, affecting food system activities and outcomes. However, for the purposes of this thesis, nutrient sustainability is operationalized through the nutrient economy, which is broader than mere nutrient availability and cycling. A sustainable nutrient economy is instrumental to sustainability of a food system, while food system structures and functions influence how sustainable a nutrient economy is. Since the Second World War, the expansion of food production, largely 'thanks' to Haber-Bosch nitrogen fixation and the use of mineral phosphorus, has occurred at the cost of a growing sustainability gap in the nutrient economy (e.g. see Figure 5 for the anthropogenic creation of reactive nitrogen), which has at least two environmental determinants, based on provisional and regulatory service-aspects. Moreover, as food is a basic human need, it is essentially linked to food security. The challenge of future food security is three-pronged: 1) matching the demand of a growing

[7] The food price crisis in 2008-09 was the culmination of a number of events: rising oil prices, growing biofuel demand, growing Asian demand, declining funding in research and development in agriculture, slowing down of yield growth rates, low stocks, macroeconomic imbalances, financial speculation, droughts, export restrictions, as well as traditional trade shocks that have a larger effect on the currently tighter global food system (Headley, 2010). Thus, uncertainty and insecurity are in-built properties of the current food regime (Headley, 2010; van der Ploeg, 2009; Lang, 2010).

affluent population to its supply, 2) doing this in an environmentally sustainable way, and 3) finally ending hunger (Godfray et al., 2010). In other words, food system research must address three individual, yet intertwined issues of availability, sustainable scale and equitable distribution of food.

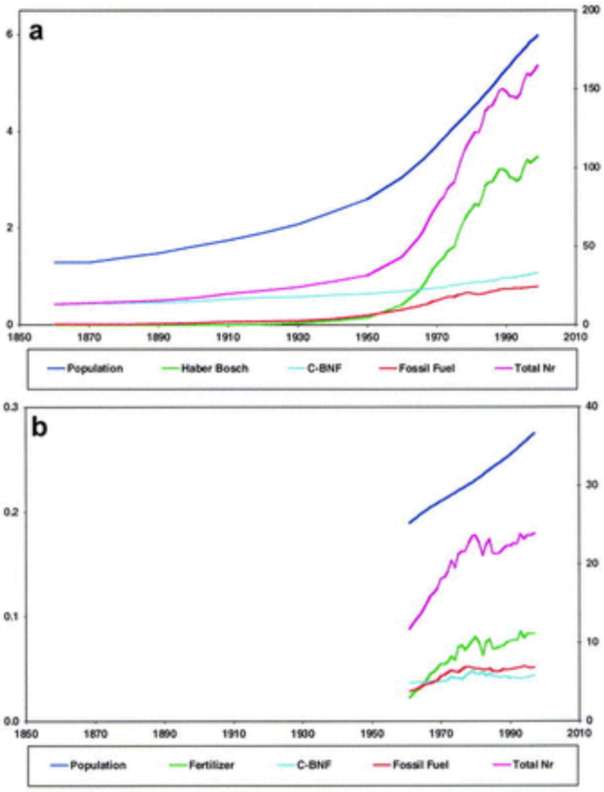

Figure 5: (a) Global population trends in relation to resource use and (b) US population trends in relation to resource use: fertilisers, biological nitrogen fixation (C-BNF), fossil fuel and total reactive nitrogen Nr[8]

Nutrient availability refers to the provisional services to the food system, which can be assessed by how many digestible food calories can be supplied to the people. In terms of availability, N and P have different properties. N is abundant in the atmosphere, but its conversion into a reactive form consumes energy; at the moment, the amount of energy consumed is up to 1.1% of global total energy use (Dawson & Hilton, 2011), and it is estimated that over half of the current population is sustained through industrially produced nitrogen (Erisman, 2011). In contrast, P is a finite earth crust

[8] (Galloway et al., 2003)

mineral, highly dissipative, and non-substitutable in the food system (Scholz et al., 2013). Although the acute physical scarcity statements made (Vaccari, 2009; Cordell et al., 2009; Déry & Anderson, 2007), and geopolitical concerns voiced about the high concentration of reserves (Cordell & White, 2011)[9] have been refuted by taking a dynamic approach to supply and demand (Scholz & Wellmer, 2013), economic scarcity particularly affects smallholder farmers (Scholz et al., 2013). This is reflected in the regional disparity of resource use: only 10% of the world's croplands account for 32% of the global N surplus and 40% of the P surplus, Western Europe being one of the nutrient hotspots (Foley et al., 2011; Potter et al., 2010). The unequal nutrient accumulation is also triggered by final consumption and dietary preferences, which affect the amount of nutrients to be collected in the sanitation and waste system. Hence, the low total resource efficiencies (about 15-20%) of industrially converted N[10] (Erisman, 2011) (see the schematic presentation of N flows in the global food system in Figure 6), and the less than 5%[11] of human-derived P (Scholz & Wellmer, 2015) for food (see the global P flows in Figure 7), should raise in an alarming manner greater attention to recycling and closing of the nutrient loops where possible.

Apart from provisional services, nutrient cycling maintains regulatory services. Over the span of 1900-2000, human activities have increased the surplus of N in soils from 20 to 138 Tg/a, and the surplus of P from 0 to 12 Tg/a, with fertiliser N inputs growing from 1 to 83 Tg/a and fertiliser P inputs growing from 0 to 14 Tg/a (Bouwman et al., 2011). Furthermore, in reactive form, N losses into the atmosphere contribute to climate change (Howarth et al., 2002), with food systems being responsible for producing 30-35% of global total greenhouse gas emissions (Foley et al., 2011), and N and P runoff causing eutrophication, leading to more than 400 reported dead zones in water systems since the 1960s (Diaz & Rosenberg, 2008). Moreover, the food system is the main contributor to biodiversity loss (Chappell & LaValle, 2011). Therefore, growing surpluses disrupt Earth systems functioning, moving the nutrient cycling closer to the tipping point. The planetary boundary of N, 25% of the present Nr conversion, has been transgressed, while the planetary boundary of P, ten times the natural background flow into oceans, is on the thresholds of transgression (Rockström et al., 2009)[12]. Thus, the nutrient economy does not only influence and interact with the food system via the physical resource availability, but also via the resilience of environmental systems.

[9] Cordell and White (2011) raised concerns over geopolitics of supply due to the high concentration of phosphorus reserves and resources. However, Scholz and Wellmer (2013) concluded that the HHI indicator, measuring the market share inequality, places P production in the middle of other metals and minerals, and in the high category in regards to reserves. Hence, geopolitical concentration leading to supply risk is only moderate and should be taken merely as an early warning signal.

[10] This N resource efficiency rate refers to the efficiency of the food supply chain up to consumption, thus not including the post-consumption phase. Hence, it is not comparable to the total resource efficiency of P.

[11] The total resource efficiency incorporates the phosphate in mining and exploration already before it enters the market, and assumes that half of the P used in agriculture comes from natural flows (Scholz & Wellmer, 2015).

[12] Planetary boundaries should not be considered as tipping points, but rather as early warning signals that the system might be approaching a threshold, thus allowing for uncertainty (Steffen et al., 2015).

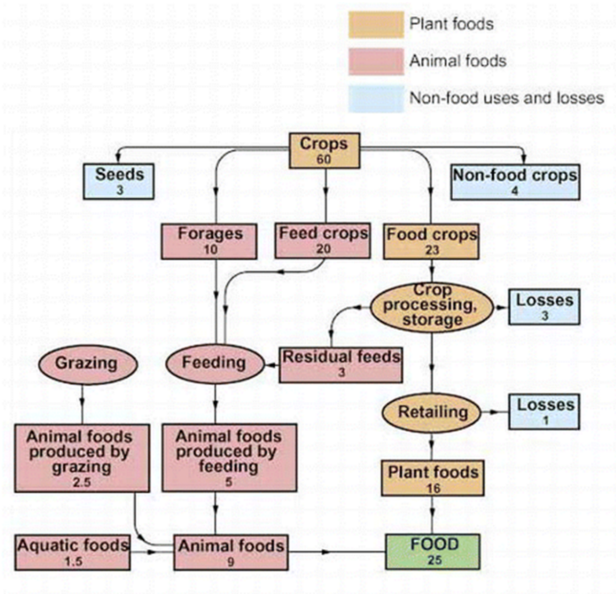

Figure 6: Nitrogen in the global food and feed harvest in the mid-1990s (Mt N/a)[13]

[13] (Smil, 2002)

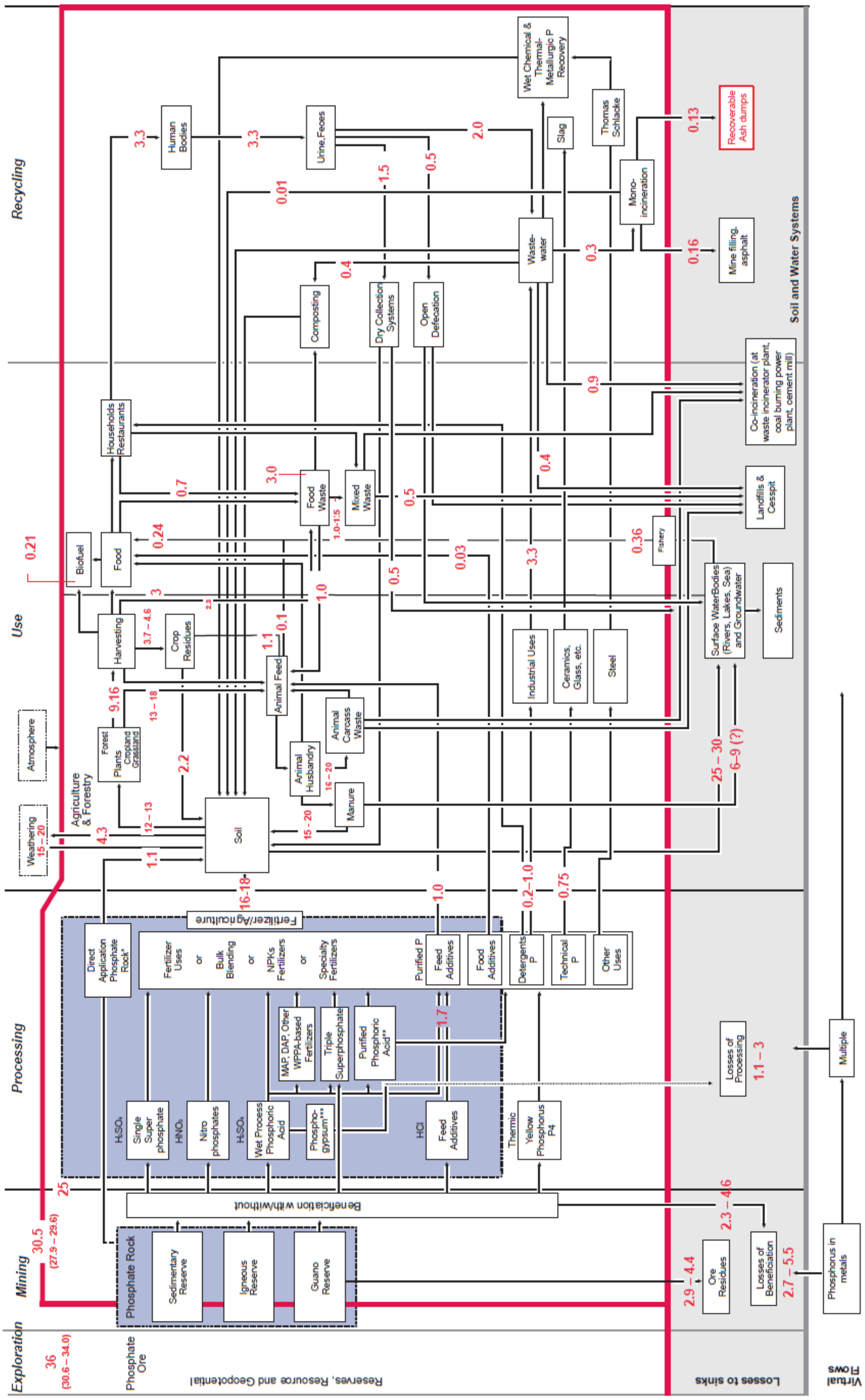

Figure 7: Global phosphorus flows (Mt P/a)[14]

[14] (Scholz et al., 2014)

4 Materials and methods

This chapter presents the materials and methods upon which the thesis and its data are based. Since the data is analysed using both quantitative and qualitative approaches, it is appropriate for the thesis author to discuss these research methodologies in depth before providing a more detailed account of the data collection, data analysis and quality of the research.

4.1 Research methodology

Sustainability science requires certain considerations, not only of the research strategy but also of the underlying assumptions regarding epistemology and ontology. This is because it is a socially constructed concept and is defined as inherently inter- and trans-disciplinary; it not only combines theories from different fields but also exists in the interface of science and practice disciplines (Scholz & Steiner, 2015). Although environmental problems can be observed, it is not the environment that has 'problems', but rather our society and social world due to unsustainable social-ecological interactions (Peattie, 2011). The shift into the Anthropocene era (the current geological period, in which human activities shape the global environment) (Waters, 2016) has led to the reinforcing inquiry into the ways in which social systems function, in order to understand the deeply embedded roots of unsustainable practices and institutions, and to find the trigger points for change. There, from being *merely* an environmental issue, sustainability has become a *societal* issue, and the interest has moved from asking questions concerning *'why this is environmentally unsustainable'* to questions of *'how society can be transformed to be more sustainable'*. This makes sustainability research distinctive in the sense that it is intentional and aims to contribute to the pursuit of sustainability rather than to only conduct research about sustainability for its own sake (Peattie, 2011). Particularly the challenge of the actual transitioning of anthropogenic dynamics calls for different types of knowledge, not only scientific, but from all key stakeholders, with researches being merely one group of stakeholders, making the research trans-disciplinary (Scholz & Steiner, 2015). While acknowledging the distinctiveness of sustainability science, it should be highlighted that only Paper IV can be perceived as an attempt at trans-disciplinary research, and even in Paper IV, stakeholders are involved for analytic rather than transformative purposes. However, it is still important to understand the distinctiveness of sustainability science, and the role of interdisciplinary problem formulation for more action-oriented future research.

Both social-ecological and socio-technical system approaches are interdisciplinary applications of understanding the complexity of system dynamics as well as system boundaries; see Table 3 below. The former analyses the social and environmental systems as separate yet inextricably coupled, and the latter analyses the social and technological as separate yet inextricably coupled. Thus, there are two epistemological assumptions based on complementarities (Scholz 2011, p. 31-39), both of which are perceived as complex adaptive systems, yet with different system boundaries. This requires epistemological pluralism, which not only refers to a complex behaviour of systems, but also to the existence of different values and goals, particularly in relation to perception of sustainability of these systems (Miller et al., 2008). Due to its background in ecology, the social-ecological approach has a more positivist nuance, relying on empirical and measurable knowledge and aiming for deterministic explanations of reality. However, as *social*-ecological hints at, it also includes interpretive knowledge. For instance, social-ecological resilience, particularly in relation to transformations, includes normativity and can be valued differently by different people (Brown, 2013). Also, the planetary boundaries approach, despite being presented as an objective measure, has a normative stance on defining the thresholds, which depends on the level of risk society is willing to take (Steffen et al., 2015). On the other hand, the socio-technical system approach relies on post-positivism and critical realism, in which reality is independent and layered, consisting of surface level ‘events’, mediating mechanisms and generative structures (Geels et al., 2016). In socio-technical system analysis, the aim of knowledge generation lies in explaining processes by analysing actions in the context of structures mediated by causal mechanisms (*ibid.*); hence, it is interpretive.

Ontological assumptions are particularly relevant to studies on system change, as they make implicit assumptions of causal agents and mechanisms, thus providing different explanations. The diversity and richness of ontologies can broaden and complement different lines of inquiries and avoid scientific imperialism, which can act towards reducing alternative views (Olsson et al., 2015; Stirling, 2011). The resilience concept focuses on negative feedback loops between social-ecological interactions and has a structural-functional ontology concerning change. In social systems, much-criticised functionalism represents continuity rather than change, consensus rather than conflict, and a rational choice of actors (Olsson et al., 2015). Hence, herein this thesis, resilience is defined in a concise way as a descriptive system property, and not as all-encompassing normative resilience thinking (Folke et al., 2010). A multi-level perspective concept is used as a descriptive and analytic framework on socio-technical change, not as a prescriptive transition management (Rotmans et al., 2001). The multi-level perspective crosses over to the ontologies of evolution theory and interpretivism, emphasising dynamic stability between incremental adjustments and radical, abrupt changes; and endogenous sense-making and learning processes between heterogeneous actors embedded in regimes (Geels, 2010). However, transition theories allow pluralism of ontologies, giving agency to different interpretations depending on the chosen perspective in a specific question (Olsson et al., 2015; Geels, 2010), and thus enabling a more comprehensive understanding of change.

Table 3: Summary of epistemic and ontological status of different papers

	Epistemology	System boundaries	System property focus	Focus on change	Motivation
I	Analytic-Descriptive, positivist	Social-ecological system bounded by social outcomes (i.e. food security) and environmental feedback loops (i.e. nutrient cycling)	Resilience of the social-ecological system, i.e. maintaining environmental system in such equilibrium that can obtain food security for all at all times	Avoidance of externally imposed environmental change	Instru-mental
II	Analytic-descriptive, positivist	Social-ecological system bounded by social outcomes (i.e. food security) and environmental feedback loops (i.e. nutrient cycling)	Resilience of the social-ecological system, i.e. maintaining environmental system in such equilibrium that can obtain food security for all at all times; Cross-scale interaction between aggregated spatial scales and temporal scales in geographically different contexts	Avoidance of externally imposed environmental change	Instru-mental
III	Analytic-description, interprevitist	Socio-technical system, bounded by food system activities (i.e. fulfilling food needs) and socio-technical feedback loops (i.e. nutrient economy)	Path-dependency and lock-in of socio-technical system, i.e. systemic resistance to systemic change for sustainability	Stimulating change by overcoming in-built resistance	Instru-mental
IV	Normative-prescriptive, interpretivist	Socio-technical system, bounded by food system activities (i.e. fulfilling food	System failures inhibiting radical change for sustainable system	Stimulating internal, radical change	Intrinsic

		needs) and socio-technical feedback loops (i.e. nutrient economy)	innovation		

4.2 Data collection

Data was collected during the years 2013-2016; see Table 4. With the exception of Paper IV, mainly the publicly available literature was used as the source of data. Paper IV collected data through an online survey that was sent to the all most relevant stakeholders in the Finnish food system during the period 2013-2014.

Table 4: Data collection modes and time frame

	2013	2014	2015	2016
Paper I	Publicly available statistical data of nutrient flows within global and Finnish society and food systems			
Paper II		Publicly available statistical data and some expert statements of nutrient flows in Finland and Ethiopia		
Paper III	Historical empirical and statistical data of Finnish post-1950s food system transition from publicly available sources			
Paper IV	Online survey to a broad range of food system stakeholders in Finland			

4.3 Data analysis

Papers I and II employed planetary boundaries approach as an analytic and theoretical framework, to refine the identified thresholds and to determine quantitatively the share of food system's impact on transgressing the thresholds in Paper I, and to add the local and the social dimensions into the framework in Paper II. Thus mainly statistical data was collected for quantitative calculation of global and local thresholds. Thresholds can be viewed as tentative estimates for operationalising ecosystem-functionality based sustainability quantitatively and objectively. The prior assessments of the planetary nutrient boundaries (Carpenter and Bennett 2011; Rockström et al., 2009) served as a starting point for a stepwise analysis, which complemented the original estimates with amendments of 1) biological N_2 fixation and fossil fuel combustion to planetary boundaries (PBs) of N, and 2) lower carrying capacity of the fresh water systems to PBs of P. In addition, an assessment was made of the share of food system in disrupting planetary nutrient flows, and of the excess flows of anthropogenic N and P flows per capita globally. Because the food system serves a critical social need, i.e. food security, planetary nutrient boundaries were translated into nutritional terms in order to exemplify the environmental limits to the way food system functions at present.

Paper II is constructed on the same grounds. The PBs of P, including the critical threshold for freshwater systems (Carpenter and Bennett 2011), and the N boundary revised by de Vries et al. (2013), Steffen et al. (2015), and Kahiluoto et al. (2014), were applied to social-ecologically contrasting local cases in Finland and Ethiopia. Socio-economic spatial variation, the current and accumulated (1900-2010) use of N and P, and P flow to water systems were estimated globally and for Finland and Ethiopia in order to assess the disparity of distribution of nutrient consumption. The excess of nutrient flows was determined as the difference between the current or the accumulated flows and the critical boundary. In addition, in the Finnish case, the PBs were reassessed locally, addressing local ecological conditions in contrast to merely downscaling global PBs to regions, nations and smaller entities. A more in-depth description of the methods used to evaluate the local PBs can be found in the article by Kahiluoto et al. (2015). Publicly available and peer-reviewed literature was used to assess the accumulated use of N and P.

Articles III-IV were based on a qualitative approach, which is appropriate when interpreting the knowledge, experiences, and interactions revealing the breadth of the phenomena under study and when analysing how and why a system operates as it does (Mason, 2002; Thorne, 2000). Qualitative research allows for being exploratory, fluid, flexible, data-driven and context-sensitive (Patton, 2002; Mason, 2002). Article III is based on case method, with the aim of constructing a historical narrative of the Finnish food regime transition, particularly in relation to the socio-technical processes inflicting changes in N and P flows within society. Various publicly available documents were used to provide rich qualitative data about the subject of inquiry and to identify meaningful events and feedback loops. In complex systems, it is crucial to have a dynamic perspective and a sufficiently wide time span, since feedback loops are not linear or easily detectable, include time delays and accumulation (Sterman, 2001). Firstly, data collection focused on each of the sub-systems of the food system: the resource base (inputs), agriculture, the processing industry, retailing, consumption, disposal (waste), and institutions, with an aim to outline the development in each one since the 1950s, particularly in relation to those processes affecting N and P in the food system. The availability, breadth and source of the data differed in each of the subsystems. Secondly, the case narrative composed by the sub-systems was used to identify the existing feedback loops. Validity and coherence were checked by triangulation of the different data sources (Creswell, 2014, 201-202).

Data for article IV was collected via a web-based survey directed at stakeholders of the food system. Stakeholders were selected with the aim of covering all parts of the food chain and nutrient economy: producers, conventional and alternative fertiliser producers, technology developers, food processors, food retailers, waste management, wastewater treatment plants, research institutes, authorities and policy-makers. A total of 222 online questionnaires were sent out. One-third (29%) of the recipients started the questionnaire, and one-fifth (20%) completed the entire questionnaire. Respondents represented a diverse range of stakeholder backgrounds: ministries or national agencies (13%), private sector (34%), research institutes (23%), development agencies (3%), the non-governmental sector (16%), consultancy agencies (8%), and other agencies (3%). Out of these, 33% represented leadership positions, 12% public servants, 23% researchers, 20% experts and 12% entrepreneurs. Exploratory desktop research was conducted for the development of the questionnaire, with both structured and open-ended questions. The analysis focused primarily on the open-ended questions, since the aim was to disclose the breadth of perspectives. Responses were coded using grounded theory principles, which rely on an inductive approach, allowing for grasping the naturally occurring themes and the constant comparative method (Charmaz, 2006). Codes were created in the NVivo program, which also facilitated coding analysis in the software. Coding progressed iteratively from specific line-by-line codes to broader categories.

4.4 Validity of the research

Validation, which seeks to establish truth in the quantitative and positivist natural sciences, is traditionally tested through either verification or falsification. However, in the applied natural sciences, to which the social-ecological approach belongs, and in social sciences, validation has a different epistemic status, with the understanding of complex relationships being the main aim of knowledge production (Scholz and Tietje, 2002, 334). Papers I and II are quantitative, and their assumptions are derived from the earth system and ecological research, accentuating the natural science background. The quality of the research depends on the validity and reliability of the assumptions regarding earth system thresholds, and whether these are accepted premises. Reliability usually refers to the replicability of tests or experiments, whereas validity refers to the accuracy and viability of means of measurements (Golafshani, 2003). In quantitative approaches especially, relevant variants of validity are construct, content, convergent and external validity (Scholz and Tietje, 2002, 336). Particularly the concepts of resilience and global scale thresholds deserve an assessment of construct and content validity, which refers to 1) the extent to which an instrument accurately measures and reflects the researcher's conception of the theoretical construct, as well as to 2) ecological validity, meaning how well the chosen proximal cue represents the case (Scholz and Tietje, 2002, 336). However, since Papers I and II only refine and build upon the existing construct, previous literature is critical for the assessment. Earth system thresholds cannot be actually measured beforehand, but can only be theoretically estimated based on measures of resilience and tipping points at lower and regional scales. Hence, global scale thresholds, particularly in the biosphere, are subject to debate and critique (Brook et al., 2013; Hughes et al., 2013), which is taken into consideration. In addition, assumptions had to be made when the necessary data was not available or precise enough, increasing the potential for errors. These are described in more detail in the actual publications.

A qualitative research approach is deployed in Papers III-IV, and the validation of the research has a different meaning and aim than in the quantitative and positivist research tradition. Broadly speaking, validation of complexity-based approaches is not truth but rather empirical adequacy (Scholz and Tietje, 2002, 334), and an ability to generate an understanding of the studied phenomenon (Stenbacka, 2001), since qualitative approach is often inspired by the different epistemology, namely interpretivism[15] (Bryman and Bell, 2015, 26, 391-425). The validity and quality of research are not viewed separately as in quantitative research; they encompass credibility, transferability and trustworthiness, as opposed to replicability, testability and stability (Golafshani, 2003). Generally, it can be asserted that reliability is a consequence of validity, hence it is enough to establish validity (Golafshani, 2003). Validation of the research in Papers III and IV is established with 1) face validation and convergent validity through consensus of the research team about the main outcomes, 2) face validation and convergent validity by the case members through communication or dialogue of outcomes with those concerned in the case study, and 3) with validation by the scientific community (Scholz and Tietje, 2002, 347). In addition, quality checks follow throughout the iteration of the research, moving back and forth between the design and implementation of the research (Morse et al., 2002). Finally, the different methods and data used in Papers III and IV ensure the internal validity and quality of the research.

[15] Interpretivism, as oppose to positivism, conceives reality as subjective and relative, hence the researcher aims to interpret the reality within its context (Bryman and Bell, 2015, 391-425).

5 Results

This section of the thesis presents the results for the research questions advanced in the first chapter. Having a distinct focus, each question fills different scientific and policy-related gaps.

5.1 Paper I: Can we feed the people: Taking planetary nutrient boundaries seriously?

5.1.1 Objectives

The objectives of Paper I were to revise the planetary nutrient boundaries and to assess the role of the agri-food systems within them. The initial assessment of nitrogen PBs included only the N_r flow induced by the Haber-Bosch process (121 Mt/a) (Rockström et al., 2009), which required amendments of N_r flow of biological N_2 fixation (40 Mt/a) and fossil fuel combustion (25 Mt/a) (Galloway et al, 2003, 2008). The planetary boundary of P is defined as 11 times the P flow into the sea in comparison to preindustrial times. The current flow into the seas is 10 Mt/a, while the boundary is set at 11 Mt/a. However, this threshold does not include P flows into the fresh water systems, which currently stand at 9-32 Mt/a. The fresh water systems are more vulnerable and their boundary is thus much lower, at only 1.2 Mt/a.

5.1.2 Findings

The current flow of reactive nitrogen is 187 Mt/a (as opposed to 121 Mt/a if only Haber-Bosch is considered), and thus a much larger amount, 140 Mt/a, transgresses the critical limit. The amendments increase the magnitude of excess flows (from 12 kg/cap/a to 20 kg/cap/a), for the PBs remain the same; that is, 25% of the current conversion to N_r. Of the N_r flows, the share of the food system is 74%, equalling 15 kg/cap/a (Kahiluoto et al., 2014). Only one-fifth of the flows occurring in agri-food systems is within the safe planetary margins, thus equalling to only 710 kcal/cap/d (see Figure 1 in Paper I). In addition, the PBs of P were complemented by the inclusion of freshwater systems, which set the critical boundary to be much lower. If fresh water systems are taken into consideration, the P boundary is transgressed by 7.8-31 Mt/a, with excess flows ranging between 1.1 and 4.4 kg/cap/a, depending on the local ecological conditions and P reservoirs. Food systems are responsible for 80% of all P flows, resulting in only 1 Mt/a of P flows in agri-food systems within the critical thresholds, and equivalent to only 250 kcal/cap/d (see Figure 2 in Paper I) (Kahiluoto et al., 2014).

5.1.3 Main contribution

The role of agri-food systems in accelerating anthropogenic N and P flows is significant. It is illustrative that under current production and consumption practices, only 710 kcal/cap/d and 250 kcal/cap/d remain within the N and P boundaries, respectively. These figures underscore that the current food systems are not sustainable and radical transformations both in production and consumption patterns are needed in order to avoid overshooting the safety limits. Although calorific daily amounts sound radical and unrealistic, even some single shifts could make a difference. A change in one's current (carnivorous) diet to a vegetarian one could double and triple the available calories under the N and P boundaries, respectively, while avoiding food waste and losses in the consumption phase would add another one-third of available calories (see Figure 2 in Paper I).

The determination of planetary nutrient boundaries contributes to global environmental change, the food system, including food security, and sustainability science research. Firstly, the planetary boundaries were complemented with nitrogen flows caused by biological fixation and fossil fuel combustion, and the eutrophication impact of P in freshwater systems, which critically lowered the estimated tolerable limits. Interestingly, ecological limits set more stringent boundaries on agri-food systems than does expected population growth and anticipated phosphorus scarcity, which have a relatively minor impact on nutrient boundaries. This implies that the functional, ecosystem-based approach to sustainability sets more stringent constraints than the resource-based approach. Secondly, the impact of food systems on disrupting global nutrient cycles is significant, which should be taken more seriously in the food security domain, as a food system is essentially a social-ecological system. Or in other words, food security cannot be achieved in the long term at the cost of deteriorating environmental resilience. Hence, food security should be understood and advocated for, first and foremost, in a social-ecological context.

5.2 Paper II: Local and social facets of planetary boundaries: Rights to nutrients

5.2.1 Objectives

The objective of Paper II was to address some of the voiced criticism directed at the planetary boundaries approach. In particular, through two spatially different contexts and temporal analysis, it was possible to grasp the issues of inequality in access to nutrients over space and time as well as the regional differences of critical thresholds when assessed in a bottom-up manner.

5.2.2 Findings

Assessment of the use of N and P in Finland and Ethiopia contrasted with use of N and P on the global scale reveals the extent of the disparity in access to nutrients. In 2010, Finnish use of N_r was 41 kg/cap, and its use of P was 2.9 kg/cap, with N_r use being one-third above global use, and P use being slightly below it. In contrast, in Ethiopia, in 2010 N_r use was 2.1 kg/cap and P use was 1 kg/cap. In Finland, fertilisers accounted for 64% of the total N_r and 74% of the total P use, while in Ethiopia, they attributed to 69% and 21%, respectively. However, when historical nutrient use is considered, the disparity is much more striking (see Figure 1 in Paper II). Accumulated global use of N_r and P per capita is 2300 kg and 200 kg, respectively; while in Finland, they are 3400 kg and 690 kg, respectively; and in Ethiopia, 26 kg and 12 kg, respectively. Thus, Finland has exceeded the global average in P use since the turn of the century, peaking in 1973, and the global average in N_r use since the beginning of the 1950s, peaking in 1974. If the global disparity and transgression of nutrient PBs are taken seriously, no further conversion of N_r or take up of virgin P can be allowed in Finland or globally. This is in contrast to Ethiopia, where N_r flow can increase, and while P flow should decrease, P use in agriculture should increase to compensate for P soil deficiency.

5.2.3 Main contribution

The planetary boundaries approach has been criticised on numerous counts. The inclusion of temporal and bottom-up approaches addresses the heretofore lacking social and local aspects of the approach. They contribute to the pleas to include cross-scale and cross-level interaction, not least in the research of global environmental change and resilience. Defining planetary nutrient boundaries in a bottom-up manner takes into appreciation the diversity and peculiarities of local ecosystems and their conditions, e.g. the sensitive Baltic Sea in Finland, which could remain ignored if planetary boundaries are only downscaled from the global scale. Hence, a planetary boundaries approach should be complemented and if needed adjusted with bottom-up assessments, which require locally derived data and expertise.

Including a temporal scale, i.e. historical accumulation of nutrient use, complements the social and spatial perspectives of planetary boundaries by highlighting the disparities of cumulated use across spatial and temporal scales. If one only projects planetary nutrient boundaries up to the current level of use, both Finland and Ethiopia are transgressing the phosphorus thresholds, but this is due to different reasons. In the former, it is mainly due to excessive P application in agriculture, and in the latter, it is chiefly due to excessive outflow of phosphorus, i.e. P depletion owing to erosion. Historical accumulation matters not least from the fact that it can aggravate path dependency into maladaptive system states[16] in both countries, resulting in a rigidity trap in Finland and a poverty trap in Ethiopia. Furthermore, historical accumulation draws in the equity of nutrient use and essentially the redistribution not only of the current use of nutrients but also of those nutrients that have accumulated in soils and water bodies. The disparity of nutrient use is much greater in accumulated nutrients than at present. Including equity of rights to disturb environmental processes and to exploit resources operationalizes the idea of environmental commons and their global governance. Considering nutrient cycling and the actual nutrients themselves as part of the common good has direct consequences on the governance of global food security, posing questions pertaining to, what the rights to common goods are and how these rights should be allocated and redistributed in the global food system, for further research.

5.3 Paper III: The need for policy to address the food system lock-in: A case study of the Finnish context

5.3.1 Objectives

The underlying hypothesis of Paper III was that the Finnish food system is locked in to an open-ended and wasteful nutrient economy. Thus, attempts since the 1970s to reverse the eutrophication of the Baltic Sea have not been successful, at least on a large

[16] Maladaptive refers to social-ecological systems' dynamics, which instead of allowing adaptation to change create persistence and stability (in the worst case trap or lock-in) in some system dimension (Carpenter and Brock, 2008).

scale. The objective was to analyse the emergence of the lock-in and identify the reinforcing processes because lock-in, the severest form of path-dependency, systematically hinders change. Hence, a better understanding of lock-in processes is critical to any future-oriented strategic and transformative action.

5.3.2 **Findings**

The current food system is locked-in by three increasing returns processes that all reinforce each other (see Table 2 in Paper III). These processes occur in production, in agri-food policy and in the food supply chain. Increasing returns are not directly associated with a particular technology or with mineral fertilisers per se (as in the case, for instance, of conventional versus electric cars); instead, they occur through multiple alignments within the regime that over time create persistent links favouring a particular type of system configuration. This renders increasing returns more prevalent and stronger, as switching paths is not merely a question of changing one technology, one process or one type of fertiliser, but rather of changing the whole architecture of the system in question, from products and processes to user practices and policies. Herein, it implies changes in the inputs and farming practices used at farm level and regional levels, adjustments in the supply chain structures, and modifications in the political and market institutions.

5.3.3 **Main contribution**

Food system lock-in contributes to the system transition and food policy literature, by highlighting the self-feeding processes that perseverate the status quo. Current research also revealed that lock-in evolved over time through several reinforcing increasing returns processes in production, consumption and institutions. Particularly in sustainability transition, system innovation and innovation literature, there is a tendency to focus on novelties and the generation of new ideas and innovations. However, lock-in forces us to direct our attention to an active and deliberate unlocking of the regime. Furthermore, since lock-in is a common systemic property and is not only prevalent in the food system but in others too, there is a need for a deepening of understanding and research into the regime unlocking, as part of the transformative action in sustainability science and sustainability transition literature. In addition, this warns against unconsciously creating increasing returns situations for one of the competing options, thus enabling a new system lock-in.

The food system lock-in highlights the institutional imbalance created over the past 50 years, which deserves more attention in the food policy domain. Agri-food related policies, on national and regional (EU) scales, mainly focus on production, which is in line with the traditional production-based division of policy sectors. However, the food market is driven by consumption, including consumers' choices and retailers' marketing strategies, which are not subject to policies. Thus, those actors and their practices, which are the most influential in the food system, are not held accountable for sustainability change, whereas producers' entrepreneurial space is constantly squeezed. Thus, there is a need, not only in the food sector, but in others too, for system policies that bridge production to consumption, accommodating at least the transparency of cost-structure, demand rather than subsidy-driven production, and the view of dynamic environmental processes.

5.4 Paper IV: Not only peasants' issue: Stakeholders' perceptions of failures inhibiting system innovation in nutrient economy

5.4.1 Objectives

As system innovation engages a broad range of actors, the aim of Paper IV was firstly to identify barriers experienced by stakeholders of the nutrient economy. Secondly, the aim was to analyse the identified barriers in a functional-structural failure framework, which enables one to link sustainability transitions to the policy-level.

5.4.2 Findings

Transition to a sustainable nutrient economy in the Finnish food system is faced with several simultaneous and reinforcing barriers, which occur at the policy-governance and enterprise-market interfaces. These barriers (see Table 2 in Paper IV) are as follows: 1) regulations, 2) policy interaction, 3) decision-making, 4) subsidies, 5) market structure, 6) infrastructure, and 7) demand. They result in a lack of governance push and a merely weak pull from the market. Specific barriers are associated with the structural and functional elements of the food system, and those barriers can cause failures, which inhibits system innovation. The agency is implicitly embedded within the practices, 'the barriers', but it is also obvious that in the policy-governance matrix, the responsible actors are mainly policy-makers; while in the enterprise-market matrix, the responsible actors are farmers, producers, retailers and consumers.

Policy governance mainly lacks direction due to structural system failures (see Table 3 in Paper IV), such as institution and interaction failures, which highlights the insufficiency of governance push. The nutrient economy does not clearly fall under the well-demarcated governance locus, and hence, there are no sufficiently consolidated and articulated pressures down the agri-food chain. At the enterprise-market interface (see Table 4 in Paper IV), there is no end-user demand. This mainly arises from the failures of market structure, infrastructure, capabilities and institutions, fortifying the idea of the weak market pull. The end users are primarily consumers, but also include farmers who use recycled nutrients. On the one hand, the market structure failure reflects the consolidation of power in the food value chain; on the other hand, it reflects the cost externalisation, resulting in that high-input food is supplied at a seemingly low price to consumers, who are not aware of all the hidden costs of food and the long-term impact of these. The weak demand is also due to the infrastructure failure: because of the regional segregation and the differing nature of the recycled nutrients, there should be alternative logistics and marketing service models to the existing ones for mineral fertilisers.

5.4.3 Main contribution

Public innovation policies and interventions are commonly justified by the market failure arguments. These failures, though, are too narrow when one considers sustainability transitions or system innovations. Hence, market failures must also be accompanied by structural and transformational failures. As for system innovation, particularly the direction and the quality of change is critical, and it is important to assess structural failures, as they relate to functional failures (i.e. transformational failures). In the empirical case of the Finnish food system, there were structural failures that lacked direction, coordination and reflexivity, and there were structural and market failures that did not generate demand, involving policymakers in the former failure and market actors in the latter one as implicit agents of change. Furthermore, it is important to detect the interplay of different failures in future research. Some failures are overlapping and overpowering, which make them persistent and ‘sticky’ even if other failures can be tackled. Such failures are likely to reside in institutions, for they are much easier to create than erase or change profoundly.

5.5 Summary of Publications I-IV

The aim of the thesis was to understand sustainability change in the food system, and complex system change in general. Broadly speaking, sustainability change is assumed to be proactive, transformative, -system-wide action in the face of uncertainty and forced global environmental change. By definition, this requires two separate yet co-evolving and cross-feeding lines of research. On the other hand, one needs to understand the processes and interaction between the environment and the social world. This determines the level of uncertainty of the forced change and anticipates what to prepare for and what to aim to avoid. In this thesis, this entailed identifying and defining the critical thresholds of nutrient cycling, within which food security could be obtained for all (cf. Paper I). Having said this, it should be asserted that thresholds are perceived rather as guiding principles than as absolute limits. They highlight the magnitude of needed change, point to what needs to be changed, and provide a benchmark for assessing and comparing different transformative strategies and actions. However, thresholds should not disguise regional and local disparities, but instead ought to be used to unlock past unequal development paths (cf. Paper II) by addressing cross-scale interaction in time and space.

The second line of research requires an understanding of how the desired change can be stimulated at various levels of society. This can be generated by inquiry into the various socio-technical structures, practices and cultures that make up the societal regime, which affects the choice and form of transformative strategies and actions to be taken. Simultaneously though, attention is placed on the socio-technical regime itself, because change is equally about the status quo and the desired future. The evolution of the status quo provides insights into what inhibits change through lock-ins (cf. Paper III), because ignorance of lock-ins can fortify the current regime instead of destabilizing it and enabling more radical change. Understanding failures in future-oriented research and linking innovative action to policies contribute to how change can be mobilised at different levels (cf. Paper IV), from governments to businesses and citizen-consumers. Technology is often given the role of instigator, enabler, and driver of change, providing the rationale for investments and subsidies into research and development. However, since technology is socially embedded in institutional structures and everyday practices, it can also act as a constraint and enforce rigidity to change, implying the need to focus on the system at large and not only the generation of technological innovation. Thus, the two broad lines of research fulfil different aims and provide different strategies to tackle the complexity of sustainability change in a comprehensive manner. Moreover, each paper contributed to a specific question in the broad picture.

Both approaches employed herein are required for facing the sustainability challenge in the food system. The social-ecological approach deals with the complexity of maintaining environmental resilience for enabling sustainability of human societies, while the socio-technical approach deals with the complexity of the sustainability transition needed in our societies. The resilience of environmental systems is a systemic property, which should be increased and not reduced, but only in reference to social outcomes, which in the case of the food system is food security for all across both space and time. Subsequently, socio-technical-system configurations can help to identify structures and practices that affect resilience, by either conserving status quo and inhibiting transition for sustainability, or inducing disruption and transforming it. Furthermore, socio-technical configurations provide the framework for the actors' practices and the context for agency (see Figure 8). Thus, sustainability change is driven by transition at multiple societal levels, with the aim to transform socio-technical feedbacks in a way that improves environmental resilience, i.e. the capacity to manage uncertainty in the long term, in reference to social outcomes.

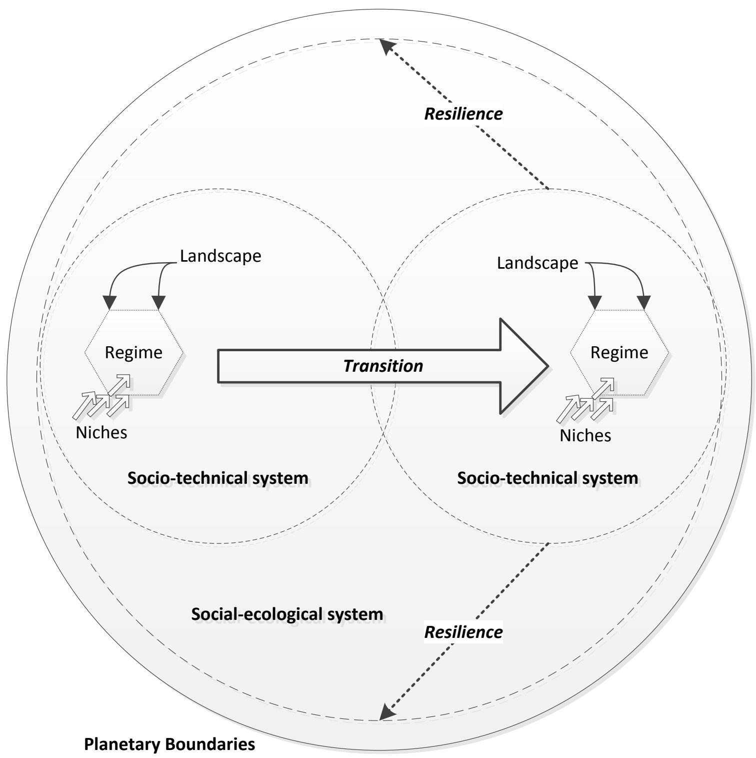

Figure 8: Combining the insights from the two approaches for sustainability change

6 Discussion and conclusions

Because sustainability change is complex and multi-faceted, understanding of it requires interdisciplinary approaches, such as social-ecological and socio-technical theoretical frameworks, that can help one to grasp not only the different hierarchical levels and scales, and interaction within and between them (Cash et al., 2006), but also the analytic diversity of problematising the same issue from different perspectives (Thoren & Persson, 2013); see Figure 9. Herein, both theoretical approaches are applications of complex, co-evolutionary and adaptive systems, the concept of resilience is instrumental in the social-ecological approach, and the multi-level perspective is in turn a framework for the socio-technical transition approach. If social-ecological analyses tend to emphasise geographically bound interaction between environmental flows and social outcomes, socio-technical analyses focus on the potential changes in practices embedded in broader societal structures and rules (Spaargaren & Oosterveer, 2012). Both resilience and multi-level perspectives may be considered as mid-range theories, and are thus criticised for not being all-encompassing and for lacking some dimensions. However, they do contribute two exclusively distinct elements to the research and understanding of sustainability change:

1. The concept of resilience introduces a measurable system property able to capture the dynamic and non-linear behaviour of ecosystem functioning and thus lay the basis for a scientifically and (in theory) objectively grounded instrument to assess environmental sustainability.
2. The multi-level, socio-technical transition framework expands our understanding of the roots of the sustainability problems (which are often due to internally structured path-dependencies), and thus expands the search for and aim of the solutions to sustainability problems. This includes not only imagining alternatives to but also critically assessing the current practices as being the outcome of and context for broader socio-technical structures. Thus, change process is co-evolution of technology and social expectations, as well as co-evolution of material artifacts and practices, mediated by formal and informal institutions and power structures.

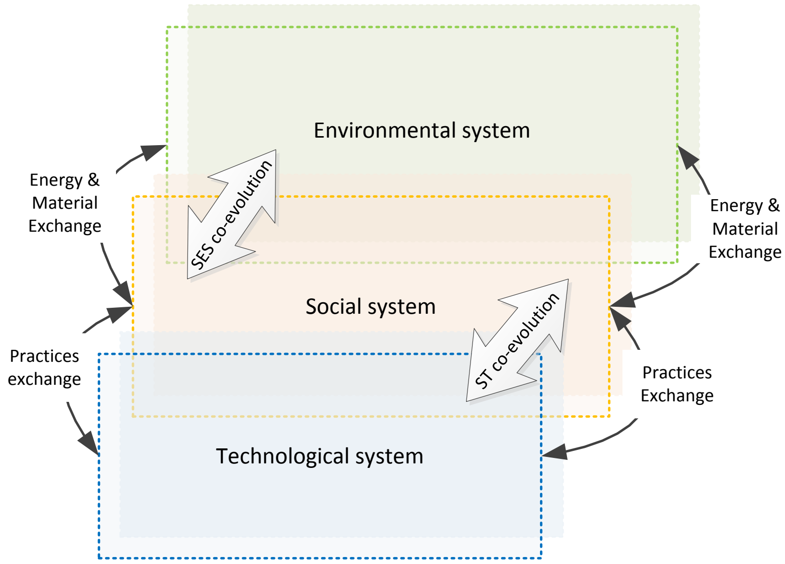

Figure 9: Multi-scale system change (SES=social-ecological system, STS=socio-technical system)

Hence, in terms of complex system change, a disparity of perspectives and incommensurability of theories lay the correct basis for the maintenance of diversity and pluralism of progress (Stirling, 2011). However, the multi-scale nature of both the transition of the socio-technical system and resilience of the social-ecological system can overemphasise a structuralist view and obscure agency. In the worst case, both concepts, in the lack of transparency of the choices and system demarcations made, could be misused for leveraging the interests of privileged groups (Shove & Walker, 2007; Meadowcroft, 2009; Brown, 2013; Robards et al., 2011; Swyngedouw, 2010). Thus, critical to both concepts is explicitness concerning the scale of resilience, i.e. the resilience of which system is to be obtained, and the scope of transition, i.e. the transition of which regime is desirable and by whom, and how the sustainability in both instances is operationalized (Olsson et al., 2015; Smith & Stirling, 2010; Fabinyi et al., 2014).

This section discusses the broader implications of the results. Its aim is to emphasise how each research question contributes to the understanding of complex system change, in terms of both scientific and policy-related contributions in the food system. Each research question approaches sustainability change in the food system from a different analytic and ontological perspective. The goal of this discussion is also to consider how the questions posed relate to each other in the bigger picture. By way of reminder, the initially posed research questions were as follows:

1. What does a planetary boundaries approach imply for the food system, when it is complemented with the inclusion of fossil-fuel combustion, biological nitrogen fixation and availability of phosphorus reserves? What is the magnitude of the needed transformation in order to return to the safe operating space?
2. What does a local bottom-up and temporal assessment of planetary boundaries varying in space entail for the food system?
3. How and what are the mechanisms that have created and maintained an unsustainable food regime resisting its change?
4. What are the failures inhibiting system innovation in the food system?

6.1 Scientific contribution to the understanding of sustainability change in the food system

Theoretical contributions:

- Paper I contributes to
  - global environmental change and social-ecological research, by reassessing the planetary boundaries of nitrogen and phosphorus;
  - food security and food system research, by determining the scale of needed transformation in order to return to a safe operating space and obtain food security in the future; and
  - sustainability science, by operationalizing and highlighting the criticality of a functional-ecosystem based approach as opposed to a resource-based perspective. This view places emphasis on environmental integrity in the social-ecological system.

<u>A pertinent question for future research:</u> What is the potential of different transformative strategies in different social-ecological contexts? How to bridge the planetary nutrient, and other (e.g. carbon and water) boundaries, while ensuring food security to all?

- Paper II contributes to
  - global environmental change and resilience research, by demonstrating that if global planetary boundaries are downscaled, they conceal local disparities in facing disturbance and local differences in returning to a safe state. Hence, the global scale must be complemented with local bottom-up assessments of resilience;

  - global environmental change and food system research, by showcasing the spatially different trajectories of nutrient use. In Finland, nutrient boundaries are transgressed due to high inflow of nutrients, while in Ethiopia, they are transgressed due to the high outflow of nutrients; and
  - the food system and food security. A temporal scale of nutrient use reveals the equity aspect of bridging the gap between the status quo and planetary boundaries. Both current nutrient use and nutrients that are cumulated in the soils and water bodies of such countries as Finland must be redistributed and allocated , if planetary boundaries and food security are to be met.

<u>Pertinent questions for future research</u>: What is the potential of nutrient redistribution and better allocation for bridging the planetary boundaries? How do global thresholds interact with locally determined planetary boundaries? How does social sustainability interact with environmental resilience across scales? How can different mechanisms in maladaptive system traps induce system lock-in?

- Paper III contributes to
  - sociotechnical transitions, environmental innovation and sustainability science research by demonstrating the rise of food system lock-in through mutually reinforcing increasing returns processes in production, consumption and institutions, and thus the need for active and deliberate regime unlocking;
  - food policy, by demonstrating that lock-in is partially reinforced by the lack of food system policy connecting consumption to production, and hence incorporating those actors and practices that are the most influential in the current food regime; and
  - sustainable innovation policy, by emphasising the need for caution in order to avoid creating and enabling situations for new lock-ins.

<u>Pertinent questions for future research:</u> What are the dynamics of deliberate regime destabilisation? What is the role of actors in maintaining the lock-in and regime destabilisation? What is the role of agency in regime dynamics and regime destabilisation?

- Paper IV contributes to
  - system innovation, socio-technical transitions and innovation policy literature by highlighting the need for including a broad range of failures, namely market, structural and transformational failures, for justification of policy intervention for system innovation. In addition, the failures need to be assessed in a structural-functional analysis, which explicates

why a given structure is a failure in terms of system innovation. This can provide the basis for linking system innovation not only to innovation policies but also to a broader policymaking context.

Pertinent questions for future research: How could innovation policies contribute to sustainability transitions? Are transition policies necessary, and if so, what is their applicable scale?

6.2 Policy implications

Taking planetary nutrient boundaries seriously, i.e. acknowledging the integrity of environmental systems, requires a more radical system transformation in the food system than what merely an environmental resource perspective would entail. For instance, instead of the anticipated phosphorus resource scarcity, the limiting factor for food security is the ecosystem functioning. Firstly, this implies that sustainability change must explicitly address the earth system boundaries, even if they are only the first-guess estimates, through a precautionary approach. Secondly, in the food system, this means that single shifts alone, such as a vegan diet or curbing all food waste, will not be sufficient to entirely bridge the gap between the current state and the safe operating space. This exemplifies the magnitude and imperative for the food system transition, yet it also highlights the broadness of transformative strategies and actions needed.

Furthermore, planetary boundaries can be useful in operationalizing the ‘new scarcity’ in the economy (Simpson et al., 2005). This scarcity does not arise from physical limits of resources, for as Schulz and Wellmar (2013) rightly pointed out, it tends to be dealt with by dynamics of supply and demand due to price adjustments. It is a scarcity that arises from the environmental system’s functional capacity that heretofore has been treated as abundant and non-critical. Because economic systems are not able to incorporate this kind of scarcity, these critical, non-substitutable ecosystem functions are over-exploited. How this should be put in place, if not through prices and restrictions, merits further research. In any case, acknowledging the non-linear behaviour of these critical functions and operationalizing their critical limits in the socio-economic system would already represent a step in the right direction.

The uncertainty of multi-scale dynamics is inherent in complex systems because the aggregate level is always more than the sum of system’s local parts, but additionally, the local parts cannot be simply downscaled from the aggregate level. This implies that learning and sharing of knowledge across levels and scales is crucial for sustainability change, particularly for the governance thereof. For instance, the growing scarcity and limits of an environmental system’s functioning forces one to consider the situation of competing interests and values in operationalizing sustainability transitions and resilience on different geographical, temporal and governance scales. Therefore, an inclusion of bottom-up assessments, based on locally sourced data, and a historical perspective on planetary boundaries, can be instrumental for bridging not only the sustainability gap, but also the social inequality gap.

The lock-in of the current food regime is reinforced by the lack of policies addressing the entire food system, integrating production and consumption and cutting through multiple sectors. Currently, in the vein of the production-based division of policy sectors, food-related policies are mainly oriented at agriculture and at regulating the environmental pollution on the supply side, dismissing the consumption and the demand side altogether. National food security policies including criteria for sustainable food systems and diets are largely missing (Paloviita et al., 2016). This does not mean that food consumption, per se, needs to be regulated, but it does spur a shift in the managerial orientation from the supply side to the demand side, because current food, and other, regimes are increasingly demand-led. By way of example, instead of regulating the agri-environmental measures to be applied in primary production, one could think of ways to impose penalties or internalise externalities of unsustainable consumption (e.g. food waste, resource-intensive products) that could be passed down the supply chain.

The role of technology in socio-technical transitions is central, but not only in the role of an enabler of and but also as a barrier to systemic transitions. In the food system, technology plays an auxiliary role, and many changes to improve overall sustainability do not require radical technological innovations at all, e.g. a shift to a vegetarian or at least less-animal-based diets or a curtailing of food losses and waste. In achieving a more sustainable nutrient economy, actors emphasise that either the necessary nutrient recovery technology is already existent or not needed at all, since some measures improving nutrient use are instead directed at changing practices in farming, for instance in crop rotation, multi-cropping and integrated production; in waste and wastewater treatment systems; and in recycling organic nutrient sources. The narrative of technological optimism can disguise these more practice-based innovations, since they are socio-economically trickier and require individual-level changes. Emphasising the incompleteness of technology can also be a strategic way to delay the needed transition, thereby maintaining the status quo. Nevertheless, particularly soft technology such as applications and ICT-based tools can be auxiliary specifically to inducing actors' change of practices. Thus, technology and technological innovation deserves being critically viewed as socially embedded into practices that generate socio-technical and environmental feedback.

The biggest barrier to sustainability change in food systems seems to lie in institutional structures that create resistance to change at both market and policy levels, by not inducing demand in the former, and by not stimulating the direction in the latter. Sustainable system innovation forces one to go beyond sector policies also to account for more macro-scale economic, research, technology and innovation policies. Although innovation research was not originally explicitly concerned with societal problems and transformations, system innovation inevitably challenges the very basic assumptions about the role of innovations and innovation policy. Misalignments originate from the fact that innovation policy tends to focus on strengthening the current regime, while transition policy pursues regime shift, which can require both phasing out some of the existing unsustainable industries and supporting disruptive innovation (Alkemade et al., 2011). Hence, while innovation is central to understanding sustainability transitions, it needs to be more reflexive of overall system functioning in terms of sustainability: not all innovation activities and R&D support is desirable, as interests in innovation for growth and innovation for sustainability can clash. Simultaneously, policies, particularly those related to strategic action, innovation, research and development, should be cautious of creating the situation of new system lock-in. This is obviously not that simple, as success of desirable technologies and options often require public support, but what is desirable in the short-term might turn into inefficiency in the long-term. Hence, system innovation policies should be concerned not only with the generation of innovations, but also with the nurturing of diversity, in an attempt 1) to avoid creating new lock-ins and the destabilisation of the regime, and 2) to break the path-dependencies and enable the formation of new practices.

6.3 Summary

The main contributions of this thesis are summarised below.

Policy implications:

- Paper I:
    - Food systems are significantly disrupting ecosystem services, namely nutrient cycling. The impact of this on food security is greater than that of phosphorus availability or population growth. Thus, food security should be treated as a matter of social-ecological interaction.
- Paper II:
    - High disparity and inequality in nutrient use occurs not only at present, but to an even greater extent if historical use is accounted for. This means that countries such as Finland have accumulated nutrients in soils and water bodies, while Ethiopia has lost its virtually negligible amount of nutrients through erosion. Hence, global redistribution and better allocation should take into account both virgin nutrients and those already embedded in organic matter.

  - Local bottom-up assessments are important in revealing local boundaries, which can be substantially different than those that are merely downscaled from the global scale. Thus, local knowledge and expertise is necessary for refining and complementing global assessments, and can provide insights for understanding different maladaptive traps.
- Paper III:
  - The lock-in of the current food regime implies a need for systematic and deliberate regime destabilisation through simultaneous action at various levels.
  - Current agri-environmental policies only address primary production, dismissing the centrality of food consumption and the agency of retailers and consumers in regime dynamics.
- Paper IV:
  - Many of the failures are related to the broader system and the system functioning per se, e.g. agri-food policy or food consumption, rather than to innovation and R&D activities explicitly. Hence, stimulation of systemic innovation in the food system requires attention to be foremost directed at the prevailing structures and practices through re-assessment of several sectoral policies, e.g. agriculture, environment, energy and waste policies, and of their coherence and directionality. Policies cutting across several sectors are essential for systemic innovation, but they require not only institutional structures but also meaningful interaction and cooperation.

6.4 Limitations of current research

Both social-ecological and socio-technical approaches may be criticised for being too techno-managerial and for lacking attention to agency, power and politics within system transitions or social-ecological transformations. To capture the wholeness of the change, it is commonly perceived and analysed at the level of aggregated patterns, whether pertaining to structures, institutions (as rules) or practices. This poses a threat of being too 'structuralist' and dismissing the agency-view. This concern is partially justified, but partially misplaced, too. Particularly in on-going regime transitions, an agency should not be downplayed, and sustainability transition literature provides avenues to do this, namely through practices that mediate structures and institutions. Yet such agency-oriented analysis requires more empirical research and better analytic tools. Practices are difficult to trace and identify when they are still in the making. That is why transition literature has thus far focused more on past transitions and why the concepts available are less useful when one analyses and explores transitions when they are in the making (Markard et al., 2012; Smith et al., 2010). Even when focusing on on-going transitions, the literature emphasises innovation and the generation of variety in niches, while the processes of selection and formation of the selective environment in the regime have not drawn sufficient attention. Having said this, it is important to note the difference between the agency driving the positive change and the agency inhibiting and preserving the existing status quo ('transformational' vs. 'conservational' forces).

The lack of agency-focus is justified, yet it can be explained by the lack of a transformational-mode of research. Actors were only included in Paper IV, and even there, mostly for analytic and not solution-oriented strategic purposes. Thus, the actual co-design and co-creation of transformative action and research was outside the scope of this thesis and is left for further research. Transformation-oriented research requires not only the engagement of different actors, but also the analysis of the arising conflicts, competing interests, and differing expectations of the actors involved. This absence, however, should not serve to downplay the interdisciplinary problem formulation, which should feed into any trans-disciplinary research. In other words, the thesis provides the solid interdisciplinary groundwork for a future trans-disciplinary mode of sustainability change research and poses research questions to be answered. In addition, arriving at an interdisciplinary research context is already challenging both scientifically speaking and from the practical perspective of engaging in and executing 'acceptable' science. Hence, while trans-disciplinary and transformative sustainability science is heralded, more efforts to reflect on the role of scientists are needed, not only in terms of studying and analysing change, but also in terms of engaging in and executing the change.

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