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Natural resource knowledge idiosyncrasy, innovation, industry dynamics, and sustainability

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Abstract

Natural resource based industries (NRBIs) have received only limited attention in Innovation Studies. In this paper we explore how qualitative diversity of ecological and geological conditions influence innovation—a phenomenon we denote natural resource knowledge idiosyncrasy (NKI)—as one particular aspect of change in NRBIs. We find that the dominant thinking in Innovation Studies about innovation and industry change—which is largely informed by studies of high-tech manufacturing industries—does not allow us to achieve a full understanding of change in NRBIs. To advance our thinking about NRBIs we propose a definition of NKI, a conceptualization of how NKI influence innovation and industry change, and explore implications of the latter for strategies for resource based development and sustainability in natural resources. Lastly, we argue that a new model of innovation is required for grasping and guiding innovation and transformation in NRBIs.

Keywords: natural resources, natural resource based industry, innovation, industrial dynamics, sustainability.

1 Introduction

It is well-known that Innovation Studies[1] suffers from a widespread high-tech and manufacturing bias (Andersen et al., 2015; Castellacci, 2008; Martin, 2013). As a result the field has comparatively little to say about innovation processes in natural resource based industries[2] (NRBIs) such as forestry, mining, oil and gas, and fishing (Andersen et al., 2015; Gu et al., 2012; Torres-Fuchslocher, 2010) which is symptomatic for a wider disregard in social science of how nature[3]—not only social factors—influence innovation (Fischer, 2016; George et al., 2015). However, innovation in NRBIs is central for achieving resource based development (Andersen, 2012; Morris et al., 2012) and for transitioning towards more sustainable modes of production of natural resources (Markard et al., 2012; Rockström et al., 2009; Wesseling et al., 2016). The increasing attention directed towards these major societal challenges over the last decade translates into a growing need for better understanding innovation in NRBIs. In this paper we set out to partly address this gap in our knowledge by exploring particularities of innovation in NRBIs.

Most existing studies of innovation in NRBIs—e.g. in wine production (M. Bell & Giuliani, 2007; Cusmano et al., 2010), aquaculture (B. W. Bell & Juma, 2007; Perez-Aleman, 2005), and oil and gas (Ville & Wicken, 2012)—treat the NRBI as an incidental context for studying generic issues as network formation or firm capabilities rather than exploring the particularities of innovation in NRBIs. The even fewer studies that do consider particularities of innovation in NRBIs (David & Wright, 1997; Katz, 2006; Marín et al., 2015; Rosenberg, 1976) rarely discuss conceptual implications of such particularities. In consequence there is a notable absence of work that explores the conceptual commonalities of innovation across NRBIs that set them apart from other industries.

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[1] We follow Martin (2012) in using Research Policy's definition of "Innovation Studies" to delimit the field to include studies "analysing', understanding and effectively responding to the economic, policy, management, organizational, environmental and other challenges posed by innovation, technology, R&D and science. This includes a number of related activities concerned with the creation of knowledge (through research), the diffusion and acquisition of knowledge (e.g. through organizational learning), and its exploitation in the form of new or improved products, processes or services."

[2] The Oxford dictionary of Economics defines natural resources as factors of production provided by nature. They belong to what is traditionally referred to as the primary sector of the economy, which also encompasses the secondary (manufacturing) and tertiary (service) sectors. We refer to the industries in the primary sector as natural resource based industries.

[3] We understand "nature" in a broad sense as encompassing the biosphere, hydrosphere, lithosphere, and atmosphere.

We will more concretely focus on how innovation often faces specific geological and ecological conditions that vary across contexts as one particular aspect of innovation in NRBIs. As Nathan Rosenberg (1976: 226) noted a while back:

"…the natural environment participates in a very direct way in the productive process. As a result, agriculture is always immersed, as manufacturing is not, in a unique ecological context".

In similar fashion Mokyr (1992: 296) argues that:

"*in mining and agriculture, what worked in one place might not work elsewhere if the topographical, climatic, or soil conditions were different. The American reaper, for example, could not be applied to the British landscape. Fertilizing, drainage, irrigation, seed selection, animal breeding, the erection of fences and hedges—all were functions of local conditions and could not be made to work universally*".

In other words, the technology underlying the input-output relationship of production in manufacturing industries such as automobiles or smartphones does, in principle, not need to vary across production sites whereas for NRBIs this relationship is never exactly the same across production sites. We follow Andersen et al (2015) in referring to this phenomenon as "natural resource knowledge idiosyncrasy" (NKI).

Acknowledging the influence of NKI on innovation leads us to pursue two sets of specific inquiries in this paper. First, although some recent studies have made notice of NKI (see Kaplan, 2012; Katz, 2006; Marín & Stubrin, 2015; Thutupalli & Iizuka, 2016), they do not attempt to conceptualize NKI and its influence on innovation, and they do not systematically explore NKI as a more general particularity of innovation across NRBIs. In this paper we attempt to narrow this specific gap in our knowledge by seeking a deeper understanding of NKI and how it influences innovation and industry dynamics across NRBIs. To inform this inquiry we analyse five strategically selected case studies that we use to advance our understanding of NKI and explore its influence on innovation and industry dynamics in NRBIs. In this we rely exclusively on secondary data.

Second, NKI appears an anomaly in front of the dominant thinking in Innovation Studies—nowhere more pronounced than in the innovation and catching-up literature—which explicitly posits that the technologies most important for industrial advance are generic and universally applicable (we elaborate on this in section 3.1).

Hence, at the outset this paper questions whether our dominant thinking about innovation—which is largely informed by studies of high-tech manufacturing industries— is suitable for fully understanding NRBIs. To examine this issue more closely we use the results from our first inquiry to discuss what NKI implies for our understanding of innovation and for what constitutes an appropriate innovation system design (or "social technology", cf. next section) in relation to two major societal challenges—resource based development and enhancing sustainability in NRBIs.

The structure of the paper is as follows. Section 2 introduces a set of key concepts that we use for reviewing and discussing the literature and for interpreting results. Section 3 highlights the shortcomings of Innovation Studies in general regarding NKI by reviewing the catching-up literature as indicative for the broader field. This exercise qualifies our interest in NKI and further substantiate the claim that the field has ignored natural resources. The section also reviews the modest number of prior contributions on innovation in NRBIs and on NKI. Section 4 describes methodology. Section 5 reviews the case studies. Section 6 analyses the case results and attends to our first inquiry while section 7 attends to our second inquiry and concludes the paper.

2 Useful concepts

The conceptual distinctions presented in this section aid us in illustrating why and in which way Innovation Studies has largely ignored NRBIs.

Firstly, we distinguish between physical technology and social technology (Nelson & Sampat, 2001). Physical technology refers to technology in the 'conventional way' associated with physical engineering and machinery. Social technology refers to particular patterns of human behaviour and social organization. Germany's industrial R&D chemical labs, Ford's organization of mass production, and Toyota's 'lean production' are examples of social technologies (Abramovitz, 1986; Nelson & Sampat, 2001). These authors argue that while imitating the technological trajectories taken by high-income countries is by no means an easy task, assembling social technologies conducive to catching-up and innovation is the main challenge of development. Social and physical technologies are thus interdependent and co-evolve. We broadly understand social technology as equivalent to a particular system of innovation.

Secondly, we introduce a distinction between generic and in situ physical technology.[4] In situ technology—or more broadly, in situ knowledge—is only useful in a specific and limited geographical area while generic technology is applicable globally.[5] Hence, in situ technology has limited diffusion potential while generic technology has vast diffusion potential. Although all knowledge has a concrete local origin in time and space, the systematic search for new knowledge is most often understood as abstracting from in situ particularities to uncover general patterns to produce generic knowledge. However, generic knowledge valid across time and place—such as geometry or physical laws—must most often be adapted to the particularities of a certain case to be applicable and useful. In addition, generic knowledge is often challenged by particular case knowledge. This implies that the ability of science and engineering to explain, predict or control phenomena rests on the ability to connect generic and in situ knowledge. The extent to which the success or efficiency of production processes depends on generic or in situ knowledge varies across industries. Some, we argue, such as software programming, will depend mostly on generic knowledge whereas fish farming—which is closer to the biological sphere—will rely more on knowledge particular to the location. Obviously, a mix of generic and in situ knowledge is required in most production processes.

Table 1: Technology typology

	Particular & in situ	**Generic & Global**
Physical technology	*Technology only useful in certain locations (e.g. the American reaper, cf. introduction)*	*Technology applicable universally (e.g. smartphone design and production technology)*
Social technology	*Particular insights (e.g. in some areas alignment between religious institutions and renewable energy technology is important for its adoption*	*General insights (e.g. institutions matter or innovation is important)*

The distinction 'particular-generic' is also relevant for social technologies. For example, institutions supporting learning and innovation are crucial for economic development (Nelson, 2008). However, such institutions take very different forms across contexts. It is thus often necessary to move into the particular context to say something meaningful

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[4] We furthermore acknowledge that these categories are relative rather than absolute which means that it is unlikely that fully generic technology and a fully in situ technology exist. Instead it is a matter of degree.
[5] We will use technology and knowledge interchangeably throughout the paper.

about institutions (Edquist & Johnson, 1997). These distinctions make up a central conceptual framework for the paper, cf. Table 1.

3 Literature review

3.1 Innovation and catching-up: the dominant model of innovation

It is commonplace, within the field of Innovation Studies, to perceive economic development as a process of catching-up where low-income countries emulate the industrial paths taken by high-income countries. Early historical studies of shifting industrial leadership highlighted how the introduction of new social technologies explained competitive advantage in the leading industries at the time (Gerschenkron, 1962; List, 1885). These studies inspired a branch of research on technology gaps, catching-up, innovation, and latecomer advantages contemplating productivity developments in post-World War 2 Europe and USA and subsequently in the 'East Asian Tiger' economies. These studies emphasize that catching-up must take place in the more rapidly-growing and technologically more progressive industries of the day (Fagerberg & Godinho, 2005).

The catching-up dynamics in East Asia have been portrayed as flock of flying geese with Japan as the lead goose followed by first tier (Korea, Taiwan, Singapore, Hong Kong) and second tier (Malaysia, Thailand, Indonesia, and even China) birds. The flying geese model conveys a linear stages-model of dynamic comparative advantage which depends on innovation in the lead country and absorptive capacity in follower countries (Kasahara, 2004). Even though the model has been widely criticized for overlooking central aspects of East Asian catch-up (Hobday, 1995), it has become very influential and is widely understood as a generic model for catch-up and innovation (Lin, 2012; Mathews, 2006). It posits that catching-up is roughly a three-stage process. It begins with the copy, replication, and reverse engineering of existing technologies developed by lead firms in high-income countries. Subsequently firms in low-income countries move on to creative imitation (i.e. making minor improvements to the original technology), and lastly they become innovators of novel items and reach the global knowledge frontier (Amsden & Tschang, 2003; Hobday et al., 2004; Kim, 1997; Lall, 1987; Mathews, 2002). We refer to this way of understanding innovation and industry development as the "dominant model".

Transfer of (physical) technology from the leader to follower countries is a central mechanism of the model. Catching-up firms and countries access this knowledge through a range of different mechanisms such as trade, inward and outward FDI, user-producer relations, joint ventures, mergers, and R&D collaborations (Archibugi & Iammarino, 2002). In consequence, transnational companies (TNCs) are—and increasingly so—seen as central conveyors of industrial knowledge from one national economy to another (Carlsson, 2006; Narula & Zanfei, 2005). A basic assumption behind this thinking is that “there is a convergence between countries in the kinds of knowledge being used” (Narula, 2003: 5) and, thus, that the relevant physical technologies for industrial advance are the same globally. Partly as a consequence, studies of catching-up and innovation have predominantly focussed on analysing the social technologies that enable access to, absorption and efficient use of key physical technologies (Nelson, 2004).

The absence of reflections on the relevance of diverse physical technologies across locations can be accounted for by the fact that catching-up in East Asia was mainly based on manufacturing industries such as shipbuilding, textiles, cars, and consumer electronics (Mathews, 2006). Such industries can produce homogeneous output given the same input factors and production process regardless of geographical location. This feature of manufacturing industries implies that the physical technology involved predominantly is generic. Indeed, it is often emphasized as a latecomer advantage that technology and “roadmaps” for catching-up already exist (Mathews, 2006). The latter perspective fits rather well with the notion that shifting techno-economic paradigms—that each has a set of key technologies at its core—drive long-run growth, and whose potential can only be exploited with new and appropriate social technologies (Freeman & Louçã, 2001; Perez, 1985). In consequence, the main tasks for social technology in fostering industrial advance in manufacturing industries include to access, absorb, and apply—often foreign—generic technology through different phases of replication, creative imitation, and lastly new-to-the-world innovation.

If one’s conceptual starting point is that a limited set of key industries are central for industrial development in each era, it is understandable that researchers focus on the social technologies required for reaping their benefits. However, it is also apparent that the dominance of such thinking—although tremendously valuable—can generate a blind spot towards innovation in NRBIs, and towards important diversity in appropriateness of in situ physical technologies.

In conclusion, our dominant thinking about innovation and development does not seem particularly appropriate for conceptualizing and analysing innovation in NRBIs.

3.2 Natural resource knowledge idiosyncrasies and innovation

Firstly, we acknowledge that several studies of innovation in NRBIs do exist. Wine (M. Bell & Giuliani, 2007; Cusmano et al., 2010) and aquaculture (B. W. Bell & Juma, 2007; Iizuka & Katz, 2011; Perez-Aleman, 2005) have for example received attention but also parts of agriculture (Ekboir, 2003; Negoita & Block, 2012) and mining (David & Wright, 1997; Wright & Czelusta, 2004). However, these contributions tend to treat natural resources as an incidental context for studying generic issues such as industrial clusters or social network formation rather than exploring the particularities of innovation in NRBIs. Indeed, most of these studies are concerned with simply demonstrating that innovation takes place in and is important for NRBIs as to counterbalance the stylized fact NRBIs are non-innovative and uninteresting for innovation scholars (see Andersen et al., 2015). Most of this literature is therefore not helpful for analysing NKI.

Instead, on the periphery of the Innovation Studies field, some economic historians (see e.g. Landes, 1998; Mokyr, 1992; Rosenberg, 1976) and agricultural economists (see e.g. Evenson, 1974; Hayami & Ruttan, 1971; Sachs, 2001) explicitly acknowledge that natural conditions—primarily in agriculture—influence technology development.

Hayami and Ruttan (1971) discuss how resource endowments—primarily in terms of land-labour ratios—influence technological choice. For example, land scarcity will lead to a focus on biological technology while land abundance will induce a focus on mechanical technology. However, focus is mainly on quantitative (how much land or how many mines?) rather than qualitative diversity (which type of land and ecosystem, or mining ore quality or rock types) of natural resources. Qualitative diversity of agricultural resources is addressed by Diamond (1999) who highlights that the diffusion of crops, animals, and associated technologies take place more effortlessly on an east-west axis than a north-south axis due to differences in natural conditions across latitudes. Locations at same latitude tend to share day length, seasonal variations, diseases, rainfall patterns, and vegetation. "*Each plant population becomes genetically programmed, through natural selection, to respond appropriately to the signals of the* *seasonal regime under which it has evolved. Those regimes vary greatly with latitude*" (ibid. p.184). By implication, both quantitative and qualitative differences complicate transfer of technology across zones with different natural conditions (Evenson, 1974; Sachs, 2001).

Moreover, there is an extensive literature—epitomized by studies on appropriate technology (Schumacher 1974) and indigenous knowledge (Mccorkle, 1989; Sillitoe & Marzano, 2009)—that champions the idea that differences in local contexts are defining for suitability of physical technologies. However, these studies predominantly focus on how idiosyncratic features of social technology (e.g. capital-labour ratios and local culture) influence innovation while geological or biological factors are not singled out as a separate dimension of appropriateness.

The notion of agricultural innovation systems (AIS) has been proposed in agricultural studies. However, this line of work mainly pursues an innovation systems perspective in agricultural studies for the purpose of understanding the organization and management of innovation processes rather than exploring the particularities of how innovation in agriculture could differ from other industries (Klerkx et al., 2012; Pant & Hambly-Odame, 2009).

Although, the studies mentioned above discuss the relationship between in situ conditions and technology development, they rarely attempt to conceptualize how qualitative diversity (not whether resources, but which) of natural resource deposits influence innovation or to generalize observations beyond agriculture.

Despite the general inattention of 'nature' in Innovation Studies a number of recent contributions have made notice of how NKI influences innovation. Most of these studies consider innovation in relation to expanding NRBIs in developing countries during the commodity super cycle that unfolded in the 2000s.

Gu et al. (2012), for example, acknowledge as a minor point that biological diversity can influence technological trajectories and that indigenous knowledge is important in these industries. Similar points are emphasized in a rather general way by Nelson (2004). Figueiredo (2010) notes that Brazilian pulp and paper producers had to follow a different technological trajectory than the leading Nordic countries primarily because the Brazilian wood source (eucalyptus) required a different type of technology. Although these studies acknowledge NKI they do not explore the issue in any depth.

Thutupalli and Iizuka (2016) and Marín and Stubrin (2015) go a step further by arguing that knowledge of in situ conditions can be an important asset for firms in NRBIs—particularly when dealing with TNCs. Kaplan (2012) shows how in situ idiosyncrasies partly explains the development of a local mining supply industry, and Iizuka and Katz (2015) argue that knowledge of in situ conditions is fundamental for efficient resource management.

A common denominator of these studies is that even though they advance our understanding of NKI, they do not attempt to conceptualize the relationship between NKI and innovation, or systematically explore it as a more general phenomenon beyond the single case study.

In this paper we review and build on these and other studies to develop a deeper understanding of NKI, and inquire further about how geological and ecological conditions influence innovation and industry dynamics.

4 Methodology

4.1 Approach

The paper applies a multiple-case study design where each case represents a separate experiment that informs our inquiries. We rely on and review existing case studies which gives our analysis a meta-level character. We use multiple cases to achieve analytical rather than statistical generalization. The former implies to sufficiently substantiate our propositions through a pattern-matching logic across selected cases. The purpose is to convincingly establish that our phenomenon of interest is also valid for other—but by no means all other—cases (Robson, 2002; Yin, 2009). The paper is thus concerned with conceptual development.

4.2 Case selection

Cases are primarily selected because they make mention NKI and its influence on innovation. By selecting cases that speak to our main conceptual interest we apply theoretical sampling of cases (Eisenhardt, 1989). We furthermore selected atypical rather than representative cases (among innovation analyses of NRBIs) to get the richest information possible on our phenomenon of interest (Flyvbjerg, 2006).

We know from previous studies that producers of natural resources constitute a mix of supplier-dominated and scale-intensive firms (Pavitt, 1984) that predominantly innovate in interaction with technology suppliers. In consequence, innovation in NRBIs hinges on interactive learning between natural resource producers and their technology suppliers (Andersen et al., 2015). The related emergence of domestic technology suppliers is a central part of a resource based development path (Torres-Fuchslocher, 2010; Ville & Wicken, 2012). The success of these key processes often rely on the creation of a supporting system of innovation (Andersen, 2012). These insights imply that to understand innovation in NRBIs we must focus not only on natural resource producers but also include their technology suppliers and the context in which they operate. These issues also informed our selection of cases where we primarily focus on innovation in technology suppliers.

We analyse two cases of agriculture (soy seeds, Argentina, and cotton seeds, India), one case of aquaculture (salmon, Chile), one case of mining, South Africa, and one of oil and gas, Norway. In Table 2 we present a case overview and summary of findings. As sources of data, we use secondary material such as scientific articles and books, and industry reports.

4.3 Case analysis

We pursue our analysis in two main steps corresponding to our two main inquiries, cf. introduction.

In the first step we use the case material to seek a deeper understanding of: (i) the content and form of NKI; (ii) how NKI influences innovation in NRBIs, and (iii) how NKI influences industry dynamics in NRBIs. We explore these three interrelated issues in each case. See Figure 1 for illustration of research design. We added a column for "technology" to enhance readability of the table. Although they are interdependent processes, we distinguish between innovation and industry dynamics, respectively, in the case review to present a more granular account of NKI's influence on them. We further analyse our findings from the cases in section 6 where we propose a definition of

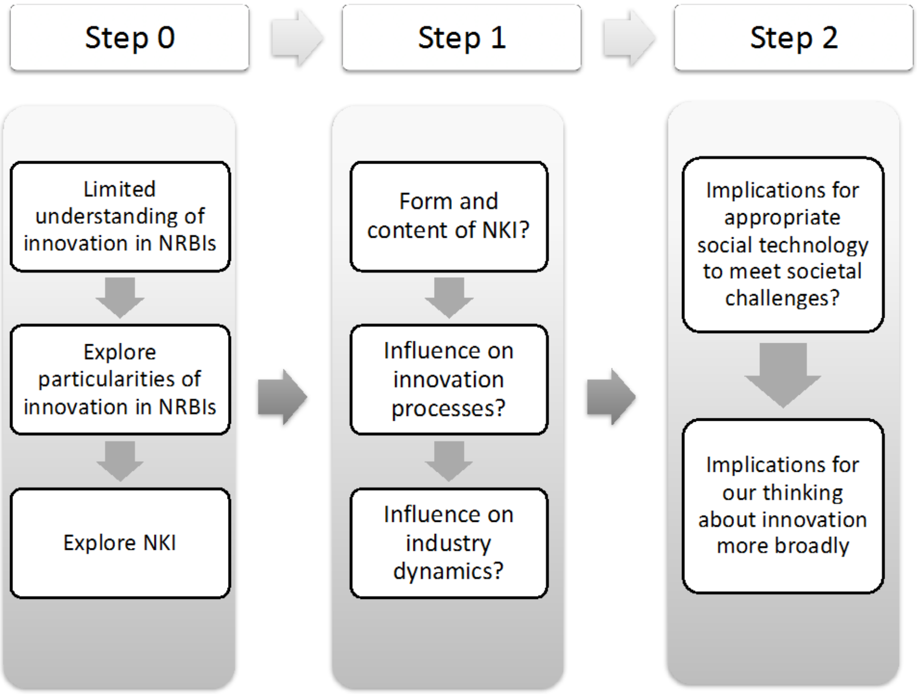
Table 2: Overview and summary of case studies

Case	Form of Natural resource knowledge idiosyncrasy	Technological focus	Influence on innovation	Influence on industry dynamics	Key references
Soy seed, Argentina **Cotton, India**	A mix of plant characteristics (resource properties), soil conditions (environment), and climate e.g. precipitation and photosynthesis.	• Genetic engineering • Combining generic traits & In-situ adapted seed varieties	• NKI enhances efficiency in natural resource production • NKI facilitates development of NKI appropriate technology	• NKI limits market size which discourage TNC investments in NKI • TNCs try to overcome NKI to reap scale economies • Domestic firms use NKI as competitive advantage against TNCs • NKI opens for participation of local firms	(Marín & Stubrin, 2015) (Thutupalli & Iizuka, 2016)
Salmon, Chile	A combination of fish variety (resource properties), water quality, salinity, microorganisms (environment), and temperature (climate)	• Breeding technology • Sanitary technology	• Lacking understanding of NKI inhibits sustainable management of local ecological systems, and, thereby, efficient production • Lacking understanding of NKI inhibits development of NKI appropriate technology and adaptation of foreign technology	• Lacking understanding and use of NKI generates industry crisis • Lacking understanding of NKI limits opportunities for local firm participation	(Katz, 2006), (Iizuka & Katz, 2015)
Mining, South Africa	A mix of special geological environment (depth) and mineral resource properties	• Drilling, ventilation and automation technologies	• NKI enables domestic firms develop appropriate technology • NKI facilitates heightened production efficiency needed for commercial viability	• NKI opens for participation of local firms in supply chain segments where NKI is strong. • TNCs dominate segments where NKI is weak and competition is based on scale economies and generic technology.	(Kaplan 2012), (Lydall, 2009)
Oil, Norway	A mix of oil purity and thickness (resource properties), extreme temperatures (climate), and sea currents and high waves (environment)	• Field exploration technology • In situ geological knowledge • Drilling/ production technology	• NKI enhances efficiency in natural resource production • NKI enhances safety in natural resource production • NKI facilitates development of NKI appropriate technology	• NKI opens for participation of local firms in supply chain segments where NKI is strong. • TNCs dominate segments where NKI is weak and competition is based on scale economies and generic technology. • It is a goal for firms/TNCs to overcome NKI to reap scale economies	(Bridge, 2008; Ryggvik, 2013; Wright & Czelusta, 2004)

NKI and a conceptualization of how it influences innovation and industry dynamics in NRBIs.

In the second step (section 7) we build on our previous proposals to discuss what NKI implies for our understanding of what constitutes appropriate social technology (or innovation system design and tasks) for NRBIs in relation to two major societal challenges—resource based development and enhancing sustainability in NRBIs. Lastly, we draw on our prior efforts to summarize how innovation in NRBIs differs from innovation in manufacturing industries and what this means for our thinking about innovation more broadly.

Figure 1: Research design



5 Case study review

5.1 Agricultural industry

Several agricultural industries have undergone profound change over recent decades partly due to progress in biotechnology. Modern biotechnology is dominated by a few transnational corporations (TNCs)—the Gene Giants (Monsanto, Syngenta, Novartis, Bayer, BASF and Dupont)—that hold the majority of patents and dominate the world market for transgenic events (e.g. a gene that confers plants' resistance to draught or to a certain herbicide) (Marín & Stubrin, 2015; Murray Fulton & Giannakas, 2001).

Currently the process of developing genetically modified plants can be separated into five steps: isolation of the gene of interest, gene transfer, regeneration, hybridization for agronomic fit, and regulatory testing. While the first three steps demand predominantly generic technology (genetic engineering techniques) and can be carried out in a laboratory, the last two steps rely fundamentally on in situ knowledge about locally adapted plant varieties and ecological conditions (Thutupalli & Iizuka, 2016). The genetic engineered traits (patented by TNCs) only become economically valuable when they are introduced into existing seed varieties adapted to specific local ecologies. Hence, despite the advent of modern biotechnology, NKI remains an important factor for innovation.

In the Argentine seed industry NKI (knowledge about local ecology and adapted plant varieties) affects innovation in two ways. First, NKI implies that the market for (transgenic) seeds adapted to local ecologies is of a limited size. At the same time, it is very costly to develop transgenic events and equally costly to patent them (Marín & Stubrin, 2015). These costs exclude most firms from entering the biotech seed market. The combination of high cost and limited market size imply that biotechnology TNCs, in general, seek to develop mainly transgenic events that have generic application and thus a larger market (Glover, 2008). Indeed, they seek to impose their products—predominantly developed for the NKI of North America—onto global agricultural markets even though they are obviously inappropriate (Naylor et al., 2004; Schneider & Gill, 2015).

Second, and partly as a consequence of the latter point, while TNCs dominate the market for genetic engineering, the picture is more mixed in the downstream seed markets where NKI is crucial and domestic firms and research organizations are active. Since the 1930s Argentine has gradually created a supporting system of innovation for seeds in Argentina. This collective endeavour has facilitated exploration, use and appropriation of knowledge of in-situ conditions and seed varieties that are mainly owned by domestic firms and public research organizations. The expertise and control of NKI allows domestic firms to compete against TNCs in the final seed market. Domestic firms incorporate transgenic events (under license from TNCs) into locally-adapted germplasm to generate productive new varieties—a process known as back-crossing. Command of NKI is thus instrumental for the competitiveness of domestic firms as it enhances productivity of seeds. For the same reason TNCs occasionally attempt to acquire domestic firms to access NKI. Control over NKI can therefore also be lost which, in turn, poses a range of questions for policy (Marín & Stubrin, 2015).

A rather similar development unfolded in India's cotton industry when legislators allowed for introducing genetically modified plants (transgenic events) to overcome a plant disease crisis in the early 2000s. Monsanto entered the market by establishing a joint venture with a domestic firm to engage in a process of backcrossing where Monsanto's transgenic event was combined with in-situ adapted seed varieties. Some domestic firms subsequently licensed the event from Monsanto while others developed competing events. Monsanto went on to use the joint venture as a platform to launch its own seed variety on the Indian market. However, Monsanto was unable to compete against the domestic firms to which it had licensed its technology primarily because it did not command an in-depth understanding of local ecology (NKI). According to Thutupalli and Iizuka (2016) this illustrates that although the generic knowledge related to genetic engineering is complex and costly, it is more straightforward to imitate and acquire than in situ knowledge (NKI). Partly for that reason, it is an innovation goal for TNCs to overcome NKI and thereby unlocking global markets with generic technology. This is exemplified by the vast investments by biotechnology TNCs in trying to develop multi-stress resistant plants (that could grow anywhere) (Schneider & Gill, 2015; Vanloqueren & Baret, 2009).

Both cases illustrate firstly, that NKI appears as a mix of seed/plant characteristics (resource properties), soil and nutrition conditions (local environment), and local climate such as precipitation and sunlight patterns. Secondly, that firms can use NKI as a strategic asset to engage with TNCs and that commanding NKI is crucial for being able to efficiently produce crops—especially under changing conditions e.g. pests. Thirdly, the latter also implies that control of NKI constitutes means for local firms to participate in global industries by developing technology appropriate for NKI. On the other hand, NKI is a barrier for TNCs in deploying expensive, generic technologies at large scale wherefore they actively try to overcome it. Lastly, it shows that the importance of NKI varies across segments of the industry supply chain.

5.2 Aquaculture industry

Atlantic salmon aquaculture has been successful in Chile and has since 1970s moved from consisting of technologically simple and small-scale family businesses to being dominated by large, internationally oriented, and technologically advanced companies (Perez-Aleman, 2005). Industry progress was in all years based on import of foreign equipment and fish eggs (the Atlantic salmon was introduced to Chile by humans). Domestic firms struggled persistently to adapt technology to local ecology through trial-error experiments. These processes were complicated particularly because the biological and environmental parameters (NKI)—such as water quality, temperature, salinity, and other ecological variables related to the microorganisms that populate each particular lake and marine location—vary significantly across production sites (Katz, 2006). Breeding new fish varieties take place through "traditional" hybridization rather than by use of genetic engineering (as in plants). However, there exist generic knowledge for selection and breeding to achieve better growth rate, disease resistance and product quality within a given ecological zone. The challenge for Chilean firms has been, guided by their understanding of NKI, to identify varieties of an imported fish that allows efficient production at each site.

In 2008 the industry suffered a sanitary crisis which originated from a combination of two factors. First, a virus in the fish stocks that, most likely, originated from imported eggs, and second, mismanagement of the local ecological systems which made the industry vulnerable to disease outbreaks (Iizuka & Katz, 2015).

Researchers have identified four explanatory factors for the poor environmental management. First, as the industry expanded during the 1990s and 2000s aquaculture sites started to spread southward in the country from its original location. This implied that fish farming moved into new ecological zones with different and unknown properties. Second, the growth of the industry was a political priority in Chile. Consequently, concessions for new fish farms were rushed and the, already meagre, regulation for safety and environmental impact was further slacked leading to a vulnerable situation. Third, regulatory bodies made very limited efforts to scientifically explore and understand the local carrying capacity of the different ecological zones of fish farms across Chile. Such in-situ knowledge of local ecology (NKI) is necessary for developing appropriate sanitary and environmental regulation that can guide and ensure sustainability of industry expansion. Fourth, control of NKI is needed to satisfactorily adapt imported technology to local conditions. Concretely, this concerns different optima in maximum geographical concentration between cultivation sites, and in methods of how to deal with fish health (e.g. antibiotics in Chile, and vaccine in Norway) (Iizuka, 2016; Katz, 2016).

From this case we see, firstly, that NKI here takes the form of a mix between species/resource properties (fish variety), local environment (water quality, salinity, microorganisms), and local climate (temperature), and that this varies across production sites. Secondly, without proper understanding and application of NKI, production of natural resources is not profitable/efficient beyond the very short run. Thirdly, we see—here by negative example—that NKI is important for formulating rules to ensure sustainable natural resource management and, fourthly, for informing development of appropriate technology by domestic supplier firms.

5.3 Mining industry

South Africa holds a large and diverse mining sector, producing more than 50 different minerals in more than 1500 mines. The industry is important in the national economy and mining is the only area where South Africa holds a significant numbers of patents with high value (Kaplan 2012). The diversity of the geological resources is one important, but partial, explanatory factor for the successful evolution of the industry. First, there is a variety of minerals as gold, platinum, coal, diamonds, manganese, chromium, copper and others that each demand distinct knowledge. Second, these minerals are not geographically concentrated but rather dispersed in smaller deposits. Third, South Africa has a unique geological environment that presents idiosyncratic technological challenges. For example, some minerals are located at far deeper depths than in any other place, which requires novel types of ventilation and automation. Fourth, the mineral resources themselves have certain idiosyncratic features that requires in situ appropriate technology to reach acceptable production efficiency (resource specificity). For example, South African platinum exists in a form, which makes production unprofitable by use of foreign technology. The same is true for coal deposits that, although abundant, are of such poor quality that it is not commercially viable using foreign technology.

In response to such challenges, domestic firms, business associations, and public research organizations established a system of innovation that by supporting mining schools and research that explored, appropriated and applied NKI to develop new technologies that made the unprofitable minerals profitable (Kaplan, 2012; Leeuw, 2012). Despite these achievements, much of the technology applied in South African mining origin from foreign companies. Domestic technology content is approximately 10-20% (Lydall, 2009). The reason is that TNCs tend to dominate segments of the supply chain where competition is based on generic technology—such as trucks and haulers—and economies of scale. In these segments, much like in agriculture, TNCs dominate, while in others, where NKI is stronger, we see more domestic firms in the market.

The case illustrates firstly that in mining NKI can be a mixture of special geological environment (depth) and mineral resource properties. Secondly, it also shows that understanding and applying NKI—via development of supporting innovation system—can enhance efficiency in production of resources to make it commercially viable. Thirdly, the latter also facilitates design of NKI appropriate technologies and participation of local firms. Lastly, we also saw that NKI can vary across segments of the industry supply chain.

5.4 Offshore oil industry

Offshore oil in Norway started in the 1960s and grew to be a highly important part of the Norwegian economy based on the ability to combine oil production with domestic industrialization via emergence of an advanced supplier industry (Ryggvik, 2013). At the outset oil exploration and drilling was performed by TNCs using technology developed for the natural conditions of the Mexican Gulf but which proved inappropriate for the North Sea (Olsen & Sejersted, 1997). The climate in the North Sea is characterised by extreme temperatures and harsh wind, current, and wave conditions that destabilised drilling vessels, created challenges for supply ships, and resulted in several severe accidents and production breakdown offshore (Hanisch & Nerheim, 1996). The inappropriateness of foreign technology, in turn, created a window of opportunity for domestic firms that went on to overcome TNC technology suppliers based on NKI appropriate technologies. The domestic technology suppliers were supported by public R&D and several oil-dedicated research institutes were created. For example, geological conditions with unique combinations of type of sandstone, and flow of water and oil drove Norwegian geology researchers to develop a new approach for oil exploration—one which was appropriate for the in situ idiosyncrasies of nature (Wright & Czelusta, 2004).

A general feature of the oil industry is that technological development is driven by the imperatives of reducing unit costs while constantly accessing new deposits that differ in terms of resource properties[6] (purity and thickness), climate (e.g. extreme temperatures), and environment (e.g. sea currents, surface and depth). Each type of deposit poses a different technical challenge to firms which limits the size of the market for a given technology and makes it difficult for firms to achieve economies of scale in oil field development (Bridge, 2008). As a consequence, technological innovation in oil is for incumbent firms predominantly about overcoming NKI by developing (generic) solutions that are widely applicable. Another consequence is that NKI, in turn, opens a window of opportunity for non-incumbent firms to enter the industry—as in the Norwegian case.

The case demonstrates that in oil NKI can take the form of a mix of oil qualities, climatic conditions as temperature, and local environment as powerful sea currents. It also shows that understanding and applying NKI is necessary for performing efficient and safe natural resource production (fewer accidents) and thus an integral part of natural resource management. We also see that NKI is essential for development of NKI appropriate technology which, in turn, facilitates participation of domestic technology suppliers in the industry. Lastly, the case indicates that economies of scale are problematic when NKI is strong.

6 Analysis and results

6.1 NKI: form and content

Based on our case analysis we propose to understand natural resource knowledge idiosyncrasy as consisting of three interacting dimensions: (i) specific resource

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[6] For example, the unusual concentration of heavy oil in Venezuela's Orinoco Belt demanded development of novel technology which subsequently boosted production and productivity (Wright & Czelusta, 2004).

properties such as plant, mineral, oil, or animal characteristics, (ii) environment including local ecology and geology as soil, rock, water salinity, and sea currents, and (iii) climate referring to weather patterns as temperature and precipitation, cf. Figure 2. The interaction between these dimensions determines the "strength" of NKI, cf. next section.

In addition, nature is not static but subject to continuous changes on the scale of a day, seasons of the year, and climate variations across decades and centuries. This last point implies that identifying, codifying and managing NKI is not a one-time event but rather a continuous process.[7]

From the case analyses we can further conclude that NKI is present across a range of diverse resource industries beyond agriculture. It is also clear that although NKI is a commonality for NRBIs, its strength varies across different NRBIs and across segments of the production chain within one NRBI. We understand strength as degree of uniqueness. If a certain set of local conditions (NKI) are found only in one place globally, we have the strongest NKI possible with limited options for widespread diffusion of technology, cf. Figure 3. When NKI is strong NRBIs require extensive in situ technology to function satisfactorily. If local conditions for a certain NRBI are the same everywhere, we have the weakest NKI possible and ample opportunity for widespread diffusion of technology. When NKI is weak production rests predominantly on generic technology with only a negligible role for in situ technology. In such cases we expect innovation and industry dynamics similar to what is described by the "dominant model", cf. Figure 3 left-sided column.

6.2 NKI and innovation

Relying on our case material we furthermore conceptualize NKI as in-situ knowledge that influences innovation in NRBIs in three important ways, see Figure 2. (1) NKI gives direction to innovation in NRBIs because it is fundamental for achieving and enhancing efficiency and commercially viability in production of natural resources. (2) NKI can also influence innovation by informing resource management regulation and standards that inter alia delimit the technological opportunity space of firms—i.e. discourage use of NKI inappropriate technology—so as to prevent production activities from collapsing

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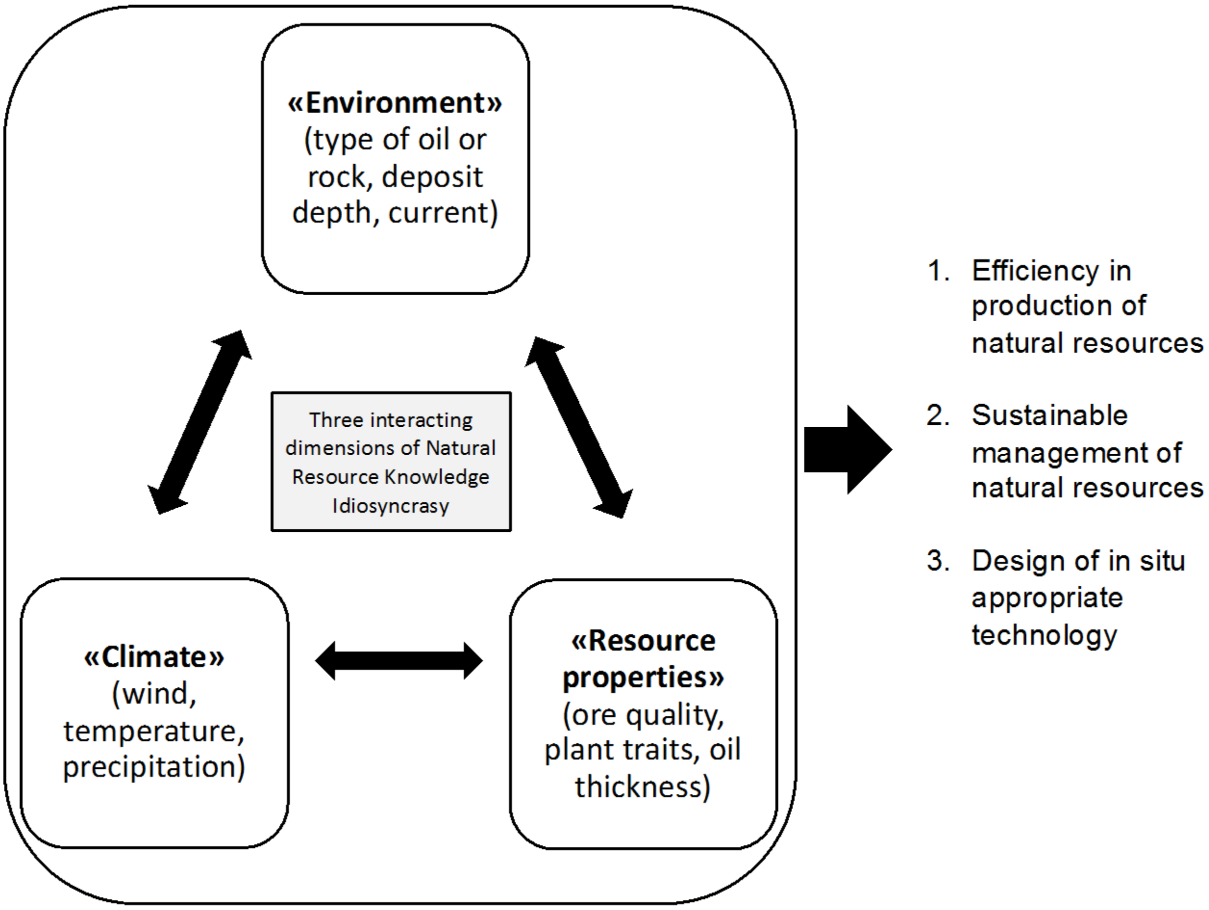
[7] In this respect, ecological systems change within shorter time spans than geology.

and keeping them within the carrying capacity of the habitat in which NRBIs are immersed. (3) A profound understanding of NKI can facilitate technological adaptation and experimentation aimed at developing (physical) technology appropriate for a given location.

Figure 2: Dimensions of natural resource knowledge idiosyncrasy



6.3 NKI and industry dynamics

We here take a step further and identify three ways in which NKI, via its impact on innovation, influences industry dynamics in NRBIs. Both pivot around the issue of how NKI influences the diffusion potential and size of the market for a given technology. Market size seems to have an inverse relationship to the strength of NKI.

First, from our case material we noted that some TNCs tend to specialize in industrial segments where NKI is weak—i.e. where technology is generic and markets are global—in order to capture the highest return possible of their R&D investments. This implies that powerful technology suppliers are incentivized to avoid areas of industries where NKI is strong and/or to ignore and override NKI by offering inappropriate technology solutions with potentially dire consequences. On the basis of these observations we can deduce that weak NKI is—seen in isolation—a factor that promotes oligopolistic and internationalized markets dominated by TNCs (as we see in many manufacturing industries). We expect that strong NKI promotes markets that are more local with better opportunities for participation of domestic firms.

Second, a combination of strong NKI and a very promising market can imply that “overcoming”—rather than ignoring—NKI becomes part of TNCs’ innovation strategy (as indicated by biotech and oil TNCs) to develop widely applicable technologies and thus expand market size.

Third, when, in the case of strong NKI, the combination of limited market size and cost of R&D deter TNCs, it opens opportunities for domestic firm participation in global industries, which then can enhance industrialization of the domestic economy. However, as it was also indicated in the case material, understanding and commanding NKI requires a system of innovation—appropriate social technology—in place to support management of NKI to the benefit of domestic firms and resource management activities.

7 Discussion

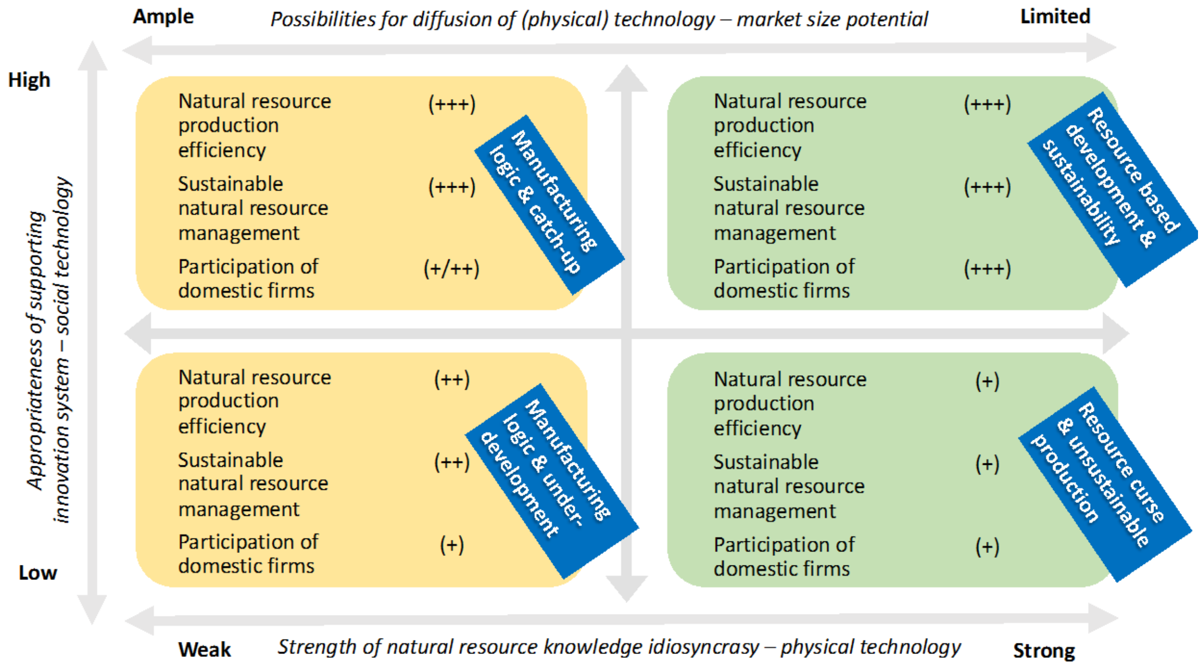
7.1 NKI and social technology

The main tasks for social technology in manufacturing industries include to access, absorb, and apply generic technology through different phases of replication, creative imitation, and lastly new-to-the-world innovation. However, social technology appropriate for NRBIs should support the following three key processes: (a) discover, map, appropriate, and retain the in-situ natural resource idiosyncratic knowledge; (b) access and absorb foreign, generic technology and combine it with NKI to create a unique knowledge base which constitutes a competitive advantage for domestic firms; and (c) apply unique knowledge base to develop in-situ appropriate technology and natural resource management practices to enhance production efficiency, sustainable resource management, and domestic firm participation in industry. If these three key activities are not supported, we consider that the social technology is "inappropriate" such as social technology for manufacturing.[8]

7.1.1 NKI and resource based development

In continuation of the previous section, different types of innovation and industry dynamics are perceivable. Figure 3 illustrates how different combinations of NKI and innovation system appropriateness can impact innovation in NRBIs. It conveys two main messages.

Figure 3: Different types of innovation and industry dynamics in NRBIs. Indicators: (+) = weak, (++) = intermediate, (+++) = strong.



First, if NKI is strong and social technology inappropriate (lower right quadrant), it is likely that a "resource curse" situation emerges with inefficient production, environmental degradation, and extremely limited participation of domestic firms.[9] However, if the social technology is appropriate (upper right quadrant), it is more likely that firms and public organizations can use NKI as a strategic asset to produce efficiently, soundly manage the surrounding habitat, and develop appropriate technologies that enable them to participate in the industry. All our case studies except Chile—which would be in the lower quadrant—are based in that category.

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[8] Obviously, the design of the innovation system is less relevant if it is "malfunctioning" due to scarce investments in innovation, corruption, or disinterested firms. Hence, we implicitly assume—on the vertical axis—that the innovation system is well-functioning.

[9] See Andersen et al (2015) for an extensive overview of the resource curse debate.

Second, when NKI is weak (left column of figure), the “dominant model” or “manufacturing logic” of innovation and industry is valid which implies that production of natural resources can rely on foreign and generic technology without major inefficiencies and negative environmental impacts on the surroundings.

In conclusion, NKI is a potential lever for resource based development, its fulfilment requires a supportive and appropriate social technology (innovation system).

7.1.2 NKI and sustainability

As a direct link between NKI and sustainability the natural change patterns of each of the dimensions of NKI are currently being transformed and accelerated by human-generated pollution and resource depletion (Rockström, 2015). It is therefore becoming increasingly challenging to understand and manage NKI. Hence, NKI is also central for climate change adaptation strategies seeking to maintain natural resource production under changing natural conditions. Moreover, as demonstrated above, the degree to which NKI is understood and applied in NRBIs can reduce energy inputs to and harmful effects of production in NRBIs. NKI is therefore also of great importance for climate change mitigation strategies.

The schematic framework depicted in Figure 3 can also be used to identify challenges for enhancing sustainability in NRBIs because inappropriate social technologies will not be able to solve the challenges confronting us.

The latter is clearly illustrated by the “green revolution” (an influential international policy and aid movement in the 1970s) which aimed at feeding the world’s poor via large-scale roll-out of stylized and, supposedly, generic but also very energy-intensive agricultural technology that had worked in developed economies. The endeavour was orchestrated according to a manufacturing logic of scale economies. Overall results were mixed but there is now widespread agreement that the energy-intensive form of agriculture is inappropriate for most ecologies as it, over time, generates a number of harmful effects such as loss of biodiversity and land degradation (Pant & Hambly-Odame, 2009; Thompson et al., 2007; Wigboldus et al., 2016).

Indeed, sustainability is today, by some communities, actually understood as reversing the green revolution ideas of basically overriding NKI by use of additional energy inputs (Lee, 2005; Thompson et al., 2007). A proactive use of NKI is equivalent to the use of in situ eco-services as production inputs rather than pesticides and chemical fertilizers (Tittonell et al., 2016).

In order to move in that direction, the diversity of NKIs must be well understood and governed. However, given many firms face disincentives to invest in NKI and that innovation systems in many (resource rich) developing countries are weak and fragmented (Lundvall et al., 2009), one can expect a tension between, on the one hand, the goals of a transition to more sustainable forms of production, and on the other, actual mode of production of natural resources. Supporting appropriate innovation systems around NRBIs in developing countries thus becomes an important task for sustainability policies. The latter is equally important for TNCs pursuing development of generic technologies (e.g. multi-stress resistant plants as energy crops) because they need knowledge about NKI in order to "overcome" it.

7.2 Implications for Innovation Studies: towards an alternative model?

The commonalities of innovation and industry dynamics in NRBIs differ markedly from those of manufacturing industries due to differences in core attributes of physical technology, cf. previous sections. The overall insight is that innovation in NRBIs often face specific geological and ecological conditions (strong NKI) that require mastering of in situ knowledge about nature. From this insight we can draw a number of tentative features of innovation processes that are unique for NRBIs.

First, natural resource knowledge idiosyncrasy (NKI) tends to limit the size of the market for a given technology which gives rise to a particular type of innovation and industry dynamics, cf. previous sections. In other words, one-size-fits-all solutions and economies of scale are often counterproductive in NRBIs whereas this is a goal in itself in manufacturing industries.

Second, in NRBIs imitation of foreign physical technology is insufficient, especially in the early phases. NRBIs require that actors explore in situ idiosyncrasies through research (genetic mapping, biology, geological surveys, etc.) and related entrepreneurial experimentation with appropriate designs of technology.

Third, the latter activity must be continuous rather than a one-time event.

Fourth, NKI varies across ecological and geological zones of different sizes. This implies that exploration of NKI must be not only continuous but also distributed according to

NKI variation. Supporting innovation systems must thus be organized as physically distributed such that it covers the range of NKI diversity within a given economy. Such system organization can be rather costly and tedious constituting a further disincentive for private investment in NKI (Evenson, 1974).

Fifth, private firms are faced with various disincentives to invest in NKI and, moreover, most firms might not be able to carry out the scientific research needed to understand NKI. These issues suggest a central role for public research organizations as the stewards of NKI, and as gatekeepers for resource based development and sustainability in NRBIs.

Table 3: Two contrasting models of innovation and industry dynamics.

	Manufacturing industry thinking (weak NKI)	**Natural resource based industries (strong NKI)**
Social technology	"One size fits all" in innovation system design	Pluralism and diversity of innovation system design
Knowledge for innovation	Generic and concentrated in a few actors	Partly in situ (local) and distributed among many actors
Market structure	Oligopolistic global market for mass-produced products	More competitive and smaller markets
Dominant firms	Few TNCs	More producers and suppliers including domestic firms
Knowledge frontier	One global frontier	Many local frontiers: exist according to geological and ecological zones
Directionality	One dominant development trajectory	Multiple development trajectories in NRBIs
Global industry evolution	Technology convergence as production efficiency advances	Technology divergence as production efficiency advances
Pathway to sustainability	One dominant pathway	Multiple diverse pathways

Sixth, on the basis of the previous points it is meaningful to argue that there in NRBIs is not one knowledge frontier to which countries must catch-up—as in manufacturing industries—but rather numerous frontiers. Indeed, each ecological and geological zone will have its own knowledge frontier, so to say. There are thus equally many different technological trajectories that industries can follow (see also Figueiredo, 2010).

Seventh, in continuation of the previous point, whereas in manufacturing industries, researchers expect to see a convergence between countries in the kinds of knowledge being used (cf. Section 3.1) to enhance productivity and value creation, we would expect the opposite in NRBIs. In NRBIs the pursuit of mastering NKI involves developing a vast diversity of in situ appropriate solutions that may not be scalable. Obviously, there is a trade-off between cost of developing appropriate technology and efficiency of production, but if such costs are ignored, divergence would result.

Lastly, in terms of enhancing sustainability in NRBIs we can expect that NKI—seen in isolation—implies that there exists a vast diversity of pathways to sustainability in terms of appropriate physical technology rather than one dominant path (as you e.g. see in transport for electrical vehicles that are technically identical globally). Hence, acknowledging NKI is one way of nuancing the complexities of socio-technical transitions (Stirling, 2011).

Combined the points emphasized above constitute a first step of formulating a taxonomy of how innovation and industry dynamics differ between NRBIs and manufacturing industries, see Table 2. In relation to our dominant thinking about innovation and industry, the taxonomy comprises the contours of an "alternative" model—a model that attempts to explicitly connect Innovation Studies to "nature".

We consider the taxonomy a first step in opening up a new agenda for understanding and analysing the particularities of innovation in NRBIs. Policy makers and analysts ought to take these particularities of NRBIs as a starting point for thinking about how to support resource based development and sustainability transitions in these industries.

8 Conclusion

We have in this paper argued that Innovation Studies have been overtly focused on studying which "social technologies" enable countries and industries to compete internationally and catch-up in manufacturing under the, often implicit, assumption that the most important "physical technologies" are, more or less, homogeneous across space. However, when biology and geology—that vary across space—become direct factors of production, what constitutes appropriate physical technologies become heterogeneous. This discrepancy implies that we have to think differently about innovation and industry dynamics in NRBIs. In this paper we have attempted to contribute to that challenge.

Our analysis and propositions in this paper serve to establish that natural resource knowledge idiosyncrasy is a commonality across the industries of the primary sector. We have offered a definition of natural resource knowledge idiosyncrasy and proposed how it influences innovation and industrial change. We have furthermore discussed the implications of the latter for innovation theory and for political strategies concerned with resource based development and sustainability in NRBIs.

In doing so we have made two contributions to the Innovation Studies literature.

First, while most prior research did not seek to theorise about NKI and its influence on innovation, we have attempted to conceptualize a particular aspect of how natural conditions influence innovation, and in doing so, supplied food for thought for future theory building activities in the field. However, our endeavour merely constitutes a first step towards exploring how NKI influences innovation and industry change in NRBIs and more research is needed.

Second, we have pointed out that the latter research activities are urgently needed because it is important to fully grasp the extent, depth, and full implications of NKI for innovation in order to prescribe sound policies for the promotion of sustainability and local development in NRBIs.

Our analysis can be extended in numerous ways. For example, researchers should engage in more extensive and systematic empirical research to find out how widespread NKI and its variation is (pursuing statistical generalization). Also, more in-depth exploration of how NKI influences innovation is needed to further test and develop our propositions. This could include questions as: Which are the key policies and strategies for managing NKI? If NKI is as important as we claim, it becomes an important issue who controls it. How has NKI ownership appropriation been managed in the past? Can our propositions about NKI be connected to the loss of global biodiversity and breach of planetary boundaries? What does NKI mean for strategy and business models of firms? We don't know sufficiently about these mechanisms.

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