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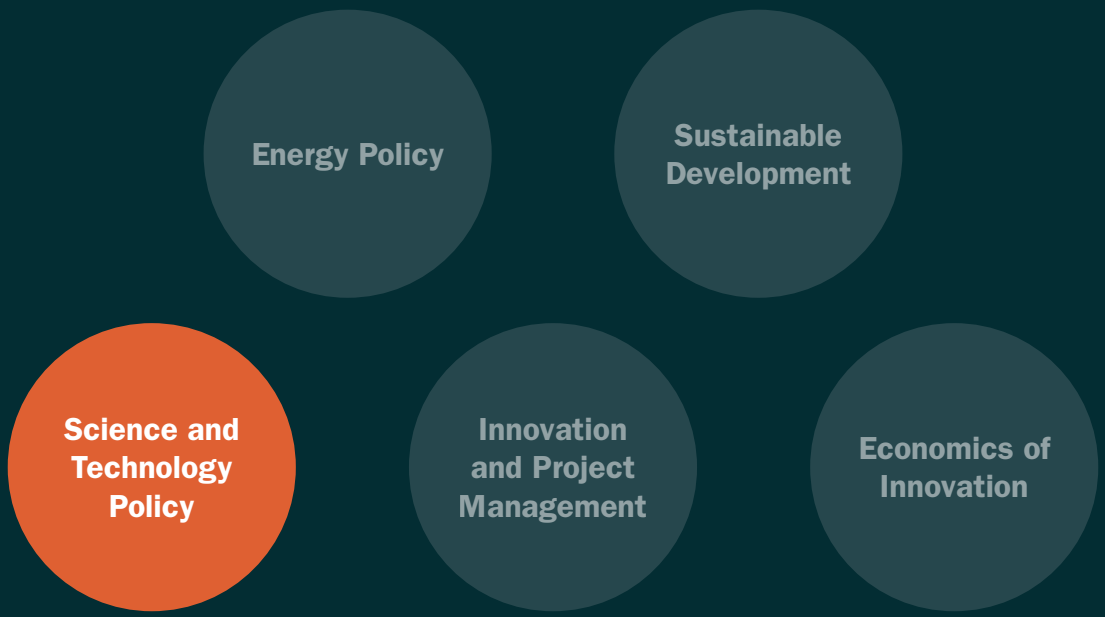

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Capabilities for Transdisciplinary Research. An Evaluation Framework and Lessons from the ESRC Nexus Network +

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Abstract Research framed to address global, grand and societal challenges has brought fresh impetus to calls by funding agencies for transdisciplinary research. Yet the urgency of such calls is not matched by sufficient knowledge of how to foster and maintain the capabilities to do transdisciplinary work. Significant gaps exist in how to cultivate and maintain transdisciplinary methods, practices and the underlying capabilities required to support them.

This paper employs a capability approach to construct a realist evaluative framework with which to assess such capabilities. The framework is operationalised through a novel three-stage mixed method procedure which seeks to evaluate transdisciplinary capabilities as they are valued and experienced by researchers themselves. The procedure is tested on a portfolio of five 'pump-priming' projects funded by the ESRC Nexus Network +.

The paper reports a set of transdisciplinary capabilities valued by nexus research participants and found to varying degrees within each of the research projects. We find that pump-priming investments are sites of research capability development in three ways; through convening cognitive capabilities; cultivating transgressive capabilities; and maintaining backstage capabilities over durations that extend beyond the beginning and end of individual projects. Furthermore, for researchers, it is the transgressive quality of these capabilities that is most salient. Directing greater attention to these different modes of capability development in pump-priming research programmes may be useful in growing and steering research system capacity towards contemporary and future societal needs.

Keywords Transdisciplinary research, research evaluation, grand challenges, sustainability, capability approach, bibliometrics

1. Introduction

Research framed to address global, grand and societal challenges has brought fresh impetus to calls by funding agencies for increased transdisciplinary research capacity (Bammer et al. 2013; Lyall & Fletcher 2013). Complex and cross-domain problems such as climate change, public health programmes, and efforts to meet the sustainable development goals, provide rationales for research design that go beyond mono- or even interdisciplinary solutions (Werlen 2015). National research councils and supranational schemes such as the European Commission's Horizon 2020 and the Belmont Forum have responded by establishing specific funding schemes to foster ongoing transdisciplinary engagements or appending specific transdisciplinary conditions to other calls.

But transdisciplinarity cannot be produced on demand. A major UK project that aimed to explore the practices and processes of transdisciplinary research was the decade-long Rural Economy and Land Use (RELU) project which receive long £26.5m of funding from the ESRC, BBSRC and NERC (Meagher et al. 2012). Reflecting on RELU, Lyall, Meagher and Bruce (2015) noted an absence of consensus on how transdisciplinary research can be achieved even when research funding encourages it. The

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capabilities that underpin such projects are not widely distributed and are significantly under-resourced in comparison to the rhetorical support they often receive. Lyall et al. call for capability-building in areas including training for early career researchers, for research leadership skills, and for the improved capability to evaluate the quality of transdisciplinary research, and indeed to learn from these as appropriate.

Recent scholarship has proposed ways in which to assess the impact and organising capacity of inter- and transdisciplinary research (Hansson & Polk 2018; Marres & de Rijcke 2020; Rafols et al. 2012). These have provided valuable insights into how to evaluate, assess and construct indicators for transdisciplinary research. However, the systematic identification and evaluation of capabilities that underpin such research has received less attention – perhaps in part because of an impact agenda logic over the last decade or so that has foregrounded the outputs of research over considerations on practice and process (Martin 2011). Addressing this gap, in this paper we ask *how can we evaluate research capabilities in transdisciplinary projects*?

Transdisciplinary research suffers from the lack of an agreed definition and concrete framework for operationalisation (Thompson et al. 2017) resulting in relatively modest cross-fertilization between teams of researchers. There is little in the way of handbooks and teaching manuals for use in the classroom, never mind for research evaluation. Research teams tend to be isolated, as are theoreticians, practitioners and methodologists presenting problems for the scope, integration and design of research (Winskel 2018). Furthermore, understandings about transdisciplinary research remain at the margins of science systems because of failures of social learning within academic communities (Bammer et al. 2013).

The scope-widening and increased complexity of transdisciplinary research leads to a number of problems and limitations for conventional disciplinary approaches. First, there are epistemic limitations of traditional knowledge production approaches, regarding the most appropriate blend of disciplinary knowledge and expertise required to address complex problems. Second, there are limits to legitimacy, regarding the credibility of scientific knowledge mobilised in societal domains. Finally, there are limitations of democracy and participation, regarding who gets to define research problems, participate in research programmes, and develop solutions (Felt et al. 2016 p. 733).

These limitations distinguish transdisciplinary research from mono-, multi- and inter-disciplinarity. Unlike circumscribed mono-disciplinarity, or hierarchically-structured multi-disciplinarity, more diverse horizontal forms of inter-disciplinarity can enable greater flexibility and robustness in systematically exploring different ways of framing and interrogating the focal problems (Stirling 2015). However, inter-disciplinarity doesn't always live up to its own claims. The intensity with which inter-disciplinary initiatives are proclaimed is not often matched by the realities of how research is incentivised or practiced in organisations (Bromham et al. 2016), and which can follow a plurality of modes and logics (Barry et al. 2008) which are in turn guided by various interests, institutions and incumbents.

Transdisciplinary research seeks to mitigate these limitations through the inclusion of non-academic partners in research design, operation, analysis, publication and the practice of attendant methods. Through engaging non-academic partners, accountability and legitimacy is created by producing scientific knowledge within the societal domain in which it is to be mobilised. Further to this transdisciplinary research projects democratise scientific knowledge by widening the scope of

participation in problem-definition, research practice, and solutions-development. Transdisciplinary research combines diverse academic expertise, foregrounds tacit knowledge, and gives voice to of a diverse set of actors including those from domains of policy, business, communities, and lay publics (Klein 2015; Lang et al. 2012; Pohl 2008; Stokols 2006).

In order to implement any given method in practice, it is necessary to hold some very particular 'capabilities' (Bozeman & Boardman 2014) which encompass both the codified practices and tacit assumptions of the method. Successful transdisciplinary collaborations require integrative, participatory and flexible methodologies (Stirling & Meyer 2001). And so, in producing knowledge by transdisciplinary means, there is a wide variety of methods that might be implemented. Transdisciplinary research represents a shift in research practices and attendant capabilities along a number of dimensions. These variously fall under both analytic and interactive kinds of disciplinary practice,[3] quantitative as well as qualitative epistemic cultures and deductive, inductive and abductive processes of reasoning. The challenge of transdisciplinary methodologies is not simply to fit different methods – underpinned by various cultures and styles of reasoning – together horizontally like a jigsaw puzzle, nor just vertically in relation to their perceived logical relationships, nor simply processually in their sequencing over time. It involves all these kinds of functions and more (Stirling 2015).

Capabilities required for transdisciplinary research are varied. They include capabilities of doing research, skills, performing methods, leadership, but also the capability to transcend and transgress disciplinary and institutional settings, to work across boundaries with a variety of expert and lay actors and interests (Klein 2010). It follows that central to transdisciplinarity is the diversity that comes with radically broadening-out research inputs not only to a variety of actors, voices and participants, but to various epistemic cultures and logics of reasoning (Knorr Cetina 2007). Furthermore, this discussion draws our attention to the often-delicate political capabilities required for integrating and fitting sticky practices and the entangled knowledge production cultures.

In order to locate, explore and assess the presence of such capabilities in the field, we propose a novel framework of evaluation. We test the framework using an embedded case study of a transdisciplinary research programme, the United Kingdom's Economic and Social Research Council's Nexus Network+.

In 2014 the ESRC Nexus Network + (NN+) was awarded £1.5m in funding by the UK's Economic and Social Research Council in order to promote the building of a network of research capabilities in examining interactions within and between domains of water, energy, and food (the WEF nexus)[4] (Cairns et al. 2017). The 'pump-priming' model included the provision of funds for further distribution over the course of several programmes of activities. The NN+ Partnership Programme was the final and most substantive programme offering five awards of between £60,000 and £120,000 each which explicitly aimed at building the capacity within the network for transdisciplinary research. We assess all five projects in the portfolio to understand what capabilities were deemed valuable for

[3] Analytic practices typically involve a closed subset of actors of particular kinds, operating according to shared narrowly-defined activities, values and commitments. Interactive methods involve practitioners engaging in implementing methods with diverse kinds of social actors, in order to elicit implications of contrasting values and commitments.

[4] See the Network's final report for details of the network's activities (Cairns et al. 2017). See UKRI funding details (UKRI 2020).

transdisciplinary research under the umbrella framework of water, energy food nexus. Summary information is provided on each of the five projects in the supplementary data, Appendix 1.

The paper proceeds as follows. In Section 2 we provide an account of the evaluative framework's theoretical underpinnings. We introduce the Capabilities Approach to assess capabilities required for transdisciplinary research. We propose a novel methodological approach in Section 3 and report findings in Section 4. We discuss the analysis and implications for theory and for policy in Section 5. Section 6 offers a short conclusion.

2. Theory

2.1 The capability approach - evaluating what researchers are effectively able to do

What are capabilities exactly, and what capabilities are required to carry out these transdisciplinary research practices? Moreover, what can an assessment of capabilities tell us that current evaluative procedures cannot? Concepts about human capabilities by development scholars such as Amartya Sen (1999) and Martha Nussbaum (2001) are useful here. The Capability Approach (CA) is a framework with which to assess institutions and practices based on one or several public values, conceptualized in capability terms (Robeyns 2016). The core characteristic of the approach is its focus on what people are effectively able to do and be; that is, on their capabilities (Robeyns 2005 p. 94). For example, we might consider the research techniques available for researchers to choose to practice– the capability to *do* ethnographic fieldwork for example, or to *be* an environmental economist.

Emerging from assessments of public values related to quality of life (Sen) and social justice (Nussbaum), the CA has been used for a range of theoretical and conceptual work (Robeyns 2016). These include small-scale project evaluation (Alkire 2005) and assessing socio-material configurations of workshops (O'Donovan & Smith 2020). Much research has been published on education and capabilities (Hart 2009; Saito 2003; Walker 2003) but rather less on the practices of research. Addressing this gap, we develop a conceptualization of capabilities for transdisciplinary research that are valued by researchers and other interested agents.

Evaluations using the CA are typically less concerned with outcomes than with locating, and allowing the possibility of intervention in, the means by which these outcomes arise. This is a crucial analytic feature of the CA where the analytic focus is on means rather than ends. Specifically, in terms of evaluation, we focus on the cultivation and availability of capabilities to act, rather than the achievements of the group being evaluated. In Section 3 we introduce a realist evaluation approach that enables us to identify the mechanisms of processes, in particular contexts, that produce sets of capabilities.

2.2 The situated and diverse nature of research capabilities

Research sites are constitutive of a diversity of knowledge, values and ultimately capabilities. The social and material contexts in which research capabilities are cultivated are multiple, patchy and heterogeneous (Pickering 1992 p. 8). Scholars in Science and Technology Studies have characterized sites of inter- and transdisciplinary research as trading zones, arenas of entanglement, arenas of interaction, knowledge or epistemic arenas, transdisciplinary knowledge spaces and temporal zones of encounter (Felt et al. 2016; Galison 1997; Knorr Cetina 1999). These concepts draw attention to the complex dynamics at play in and between "the concrete intertwinements of imaginations, expectations, structures (institutions, programs, careers, etc.), people, and values" of knowledge production (Felt et al. 2016 p. 735).

The CA provides conceptual tools capable of evaluating these complex sites. Capabilities are inevitably situated in messy socio-material settings (Oosterlaken 2011). At sites of transdisciplinary knowledge production these include offices in academic departments, disciplinary norms, methods, campus rules, research ethics frameworks, field locations and the myriad of instruments, tools, knowledges and relations at and between these sites. This milieu of social institutions, norms, environmental factors and people's behaviours are crucial conversion factors that mediate capability inputs, such as knowledge, finance, resources, goods and services and facilitate the cultivation of capabilities in a capability set (see Figure 1).

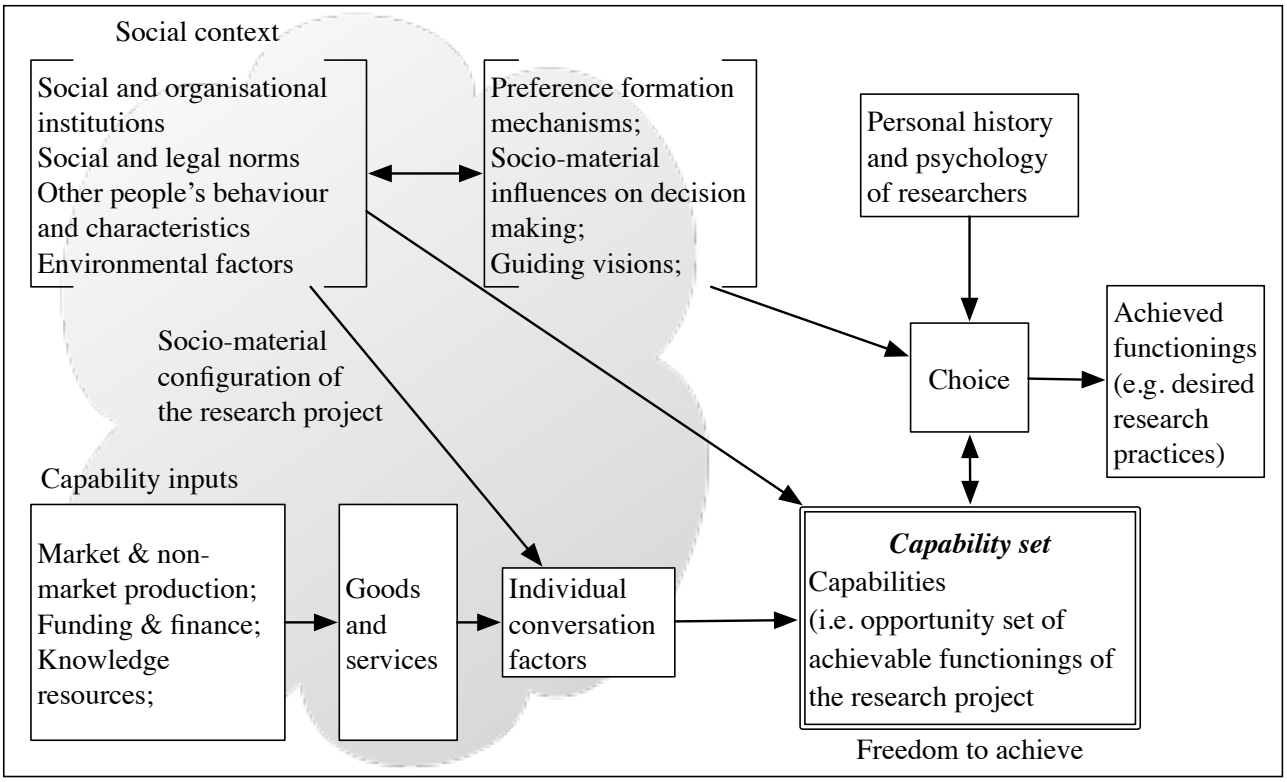

Figure 1. *Mapping the cultivation of research capabilities. Adapted from Robeyns 2005.*

Explicit apprehension of diversity is an integral property of the CA, with which Sen wanted to develop "an account of the good, which is attuned to the actual complexity of the world and the actual complexity of how human actors think about value" (Couldry 2019 p. 2). In opposition to utilitarian frameworks (the limitations of which motivated Sen's foundational works and remain dominant in many contemporary policy domains), the core evaluative logic of the CA is in taking account of the particular, the plural and the diverse. This accords with our requirements for an evaluative framework which recognizes the potential for a myriad of methodological fitting, arrangements, and values, and complexity in practicing research that transgresses social, disciplinary and institutional boundaries.

2.3 Locating and evaluating capabilities

Capabilities within transdisciplinary research projects form the evaluative space for our framework. But what capabilities matter? Our analysis follows both Sen (1999) and Robeyns (2005) in seeing the capabilities available to people as a matter of empirical identification. We are interested in learning what researchers are able to do and to be through the provision of all that is necessary for research. To be

clear, we do not inquire into achieved functionings[5] or processes of conversion (processes indicated in Figure 1). Rather, we are interested in the capabilities made available by the configuration of actors, knowledge and resources within the research projects of the Nexus Network+.

And so, to guide our exploration of these spaces, and our mapping of which capabilities matter, we propose a heuristic. We illustrate our heuristic to guide our exploration of the transdisciplinary capability spaces in Figure 2. The purpose of the heuristic is to account for a set of capabilities within the overall capability space of a transdisciplinary research project. The idea is to use this conceptually informed framework to direct our attention to where and how capabilities are most likely to be situated, whilst – following Robeyns (2005) – allowing them to emerge inductively through careful analysis.

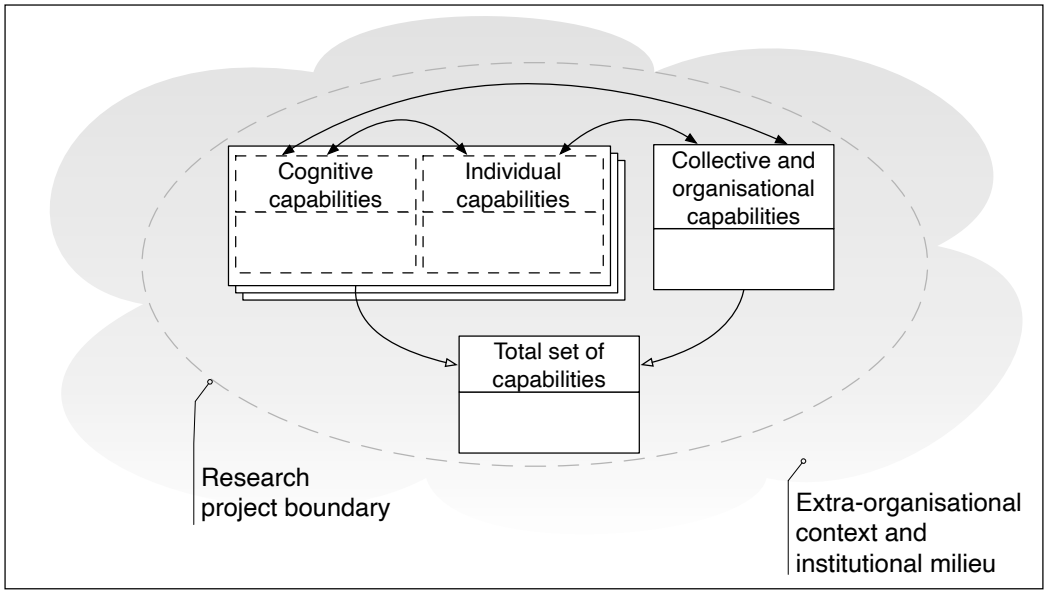

Figure 2. Heuristic relations between capabilities within a transdisciplinary research project.

We begin our heuristic with the capabilities required to perform scientific and technical work are central to transdisciplinary research. These include formal educational endowments acquired through graduate and post-graduate training, usually encompassed in concepts of 'human capital' (e.g. Becker 1964). These *cognitive* capabilities variously include the skills, aptitudes, and formally taught techniques required, for example, to take soil samples, conduct interviews, or perform econometric modelling.

At undergraduate level, and often through post-graduate training, the provision of these capabilities usually follows disciplinary lines. These demarcations are also evident in academic journals, which remain, for the most part, closely organized along disciplinary lines (Rafols et al. 2012). Indeed, the capability to publish in a disciplinary journal is one indicator of the cognitive capabilities available to researchers. Moreover, the expansion of capabilities through training in new skills is a noted impact of research in itself (Molas-Gallart et al. 2014). And so, at any research site we expect to encounter cognitive capabilities of individual researchers and other participants.

[5] The distinction between achieved functionings and capabilities is between what is actually realized - the beings and doings - and what is effectively possible - the options valued by researchers. Our focus on capabilities rather than functionings is driven by the aim of the study - to assess what possibilities for research are cultivated in the course of NN+ funding.

Capabilities for transdisciplinary research

In practice, cognitive capabilities are always augmented by the skills, tacit knowledge and experiential knowledge acquired by individual researchers (Heckman & Corbin 2016). These, are "the strategies and policies of knowing that are not codified in textbooks but nevertheless inform expert practice" (Knorr Cetina 1999 p. 2). Moreover, "expertise, of whatever kind, is based on experience of some kind, even though experience tends to be eclipsed by or subsumed under certified expertise" (Nowotny (Nowotny 2003 p. 154). In other words, 'expertise' and legitimacy in knowledge production, is based not only on cognitive capabilities, but how those capabilities are aligned with experience. Research capabilities then are the 'sum total of scientific, technical and social knowledge and skills and capabilities available to a particular individual' (Bozeman & Rogers 2001). These represent a further set of individual capabilities in our heuristic.

The production of scientific knowledge, legitimacy and individual expertise is inevitably socially held (Cuevas Garcia 2016). Moreover, "many of the capabilities [of knowledge production] are more social or political than simply cognitive" (Bozeman & Rogers 2001 p. 418). It follows that these capabilities are often cultivated and situated collectively. Pragmatically, individual researchers rarely, if ever, cultivate all of these capabilities required to carry out transdisciplinary research. Research project groups facilitate the division of labour, share expertise and contribute mutual and collective capabilities and are an every-day feature of scientific research. This presents a further distinct but related set of capabilities for our heuristic. The provision and achievement of capabilities is held, used and influenced by group, social and environmental factors (Ibrahim 2006; Stewart 2005).

Capabilities can be expanded, attained and realised as much through collective action as individual effort. Indeed, the presence of capabilities in any situation can be linked to the character and configuration of prevailing social structures and material conditions (O'Donovan & Smith 2020; Oosterlaken 2011). The implication here is that it is not merely an enrolment of high-capability individual that will contribute capabilities to a research project. But rather aggregate individual capabilities, and the addition of capabilities that arise from the configuration of people and things in a project team. Our heuristic then is constitutive of collective capabilities that that are formed across and between research groups and mediated by organisational and institutional milieu.

Finally, the capability to jointly reflect on the research topic with extra-institutional actors are considered essential to increase scientists' understanding of complex knowledge-related problems. This work takes place in often temporarily constructed shared epistemic arenas Felt et al. (2016) where researchers extract, integrate, and interpret the extra-scientific actors' knowledge. Moreover, the institutional and disciplinary boundaries need continuous stabilisation work which generally involves a variety of actors (Felt 2009 p. 46; Gieryn 1995 p. 406). The establishment and maintenance of these spaces, however temporarily, requires the cultivation of specific capabilities. And crucially, the expansion of capabilities to groups has to be realised through action that changes social structures (Robeyns 2005; Zheng & Stahl 2011).

As illustrated in Figure 1, the degree, distribution and quality of capabilities is shaped by social and environmental factors such as social institutions, guiding policy visions and regulations, part of a broader milieu common to all researchers (Stengers 2005). These may be interpreted in diverse ways, and co-produce in individuals a multitude of values and motivations contributing to differences in what capabilities are valued (Robeyns 2005). As such, we note a third distinct but related component of our heuristic, the extra-organisational and institutional milieu. These are the broader social contexts and

socio-material configurations that are at once crucial in shaping capabilities, but require structural interventions beyond individual capability if they are to change.

3. Methods

Based on our conceptualisation of transdisciplinary research projects, we need a methodology that accomplishes a series of analytic tasks.

Stage I: identify inductively a list of capabilities associated with transdisciplinary research practices. Here we combine analysis from reviews of literature and project reporting and code the human capabilities deemed necessary for such research.

Stage II: appraise how the capabilities claimed for transdisciplinary research sites are actually experienced by researchers. Here, we combine the use of bibliometric analysis, questionnaires and semi-structured interviews because in combination they permit the systematic analysis of capabilities experienced within all five Nexus Network + projects. An overview of each project is provided in Appendix 1.

Stage III: compare the capabilities in Stage I with those mapped in Stage II in order to identify expected and absent capabilities.

In combining these methods, we follow a typical evaluation pathway (Gilmore et al. 2019): establishing expectations, determining reality, locating differences – in this case between expected capabilities and those which are experienced by researchers. This section begins by motivating the overall methodological approach, demonstrating how and why an inductive and experimental framework based on the Capabilities Approach can be used within a realist evaluation.

3.1 Realist evaluation and the Capabilities Approach

The structure of a realist evaluation follows a cycle of Initial Programme Theory (IPT) development, data collection, data analysis and IPT refinement (Nurjono et al. 2018 as illustrated in Figure 3). We identify a three-step process of realist evaluation corresponding with our three-stage analytic requirements. Developing IPT begins with the compilation of an initial theory-driven list of expected capabilities for transdisciplinary research (Step 1), followed by data collection on the five cases for context and mechanisms (Step 2), then analysis of data to refine the initial programme theory (Step 3). The framework affords feedback loops throughout the process corresponding to feedback that occurs between theory, collection, and analysis (Gilmore et al. 2019; Pawson & Tilley 1997). The experimental nature of our inquiry means that while we avoid offering strong claims to generalisability or comprehensiveness, the approach enables us to gain insights into the capability space of research projects that were previously uncharted.

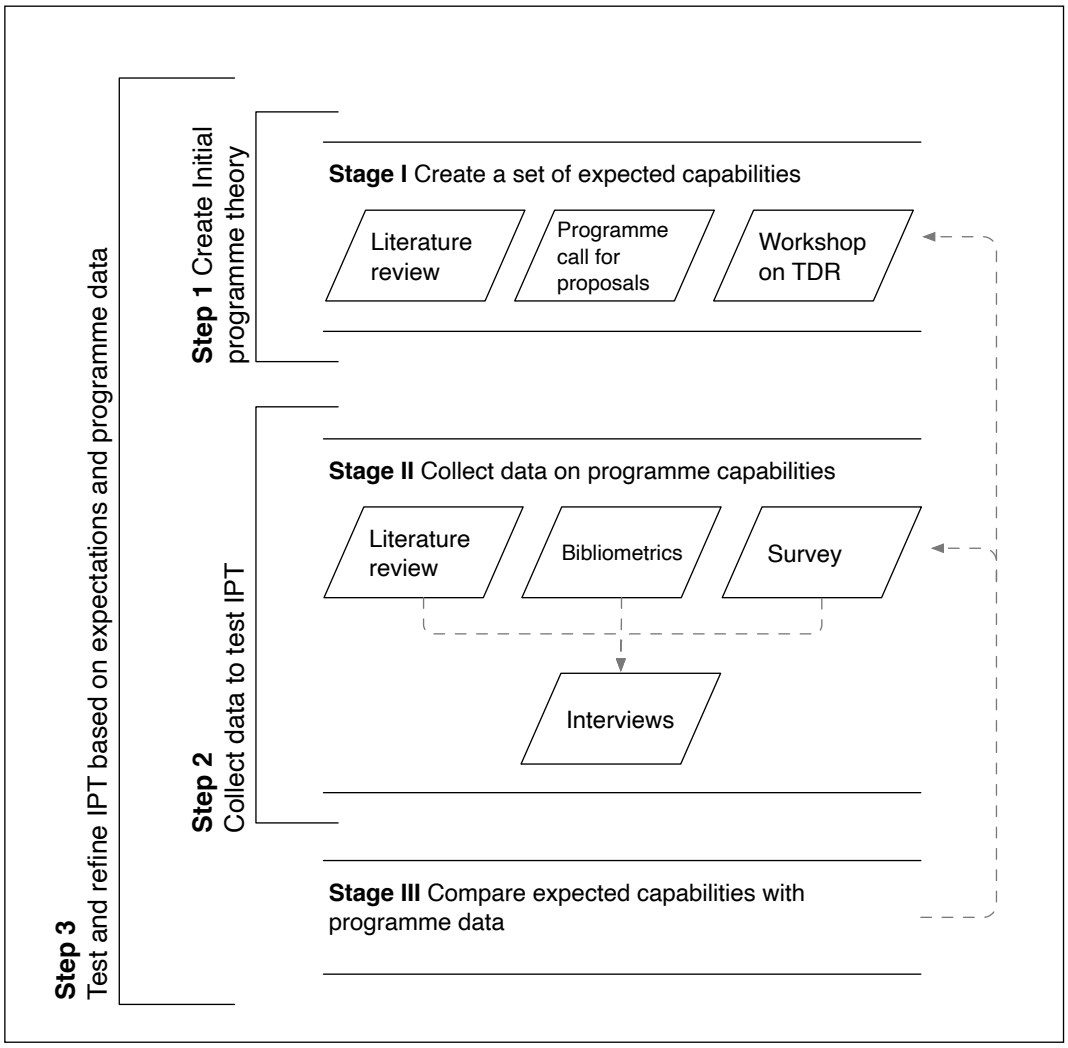

Figure 3. *Flowchart representing a cycle of Programme Theory development for a realist evaluation framework that operationalises the three-stage capability mapping framework.*

For our purposes, The Nexus Network+ is a theoretically driven, analytically interesting test case for a capability approach to research evaluation. First, it presents a single, bounded research portfolio with the explicit aim of building capabilities. Secondly, the partnership programme's call documentation provides a well-described Initial Programme Theory as to why the programme was expected to produce transdisciplinary capabilities. Finally, the recent end of the partnership projects meant that memories of the projects were somewhat fresh and the insights we could gain were more detailed as a result[6].

3.1.1 Stage I – Compiling a list of expected capabilities

Adapting the capabilities approach for analytical purposes requires careful explanation and justification of the relevant capabilities identified and the methods used. Robeyns (2003) sets out criteria for identifying sets of capabilities. They should be explicit, discussed and defended. The level of abstraction should be appropriate to the study context and project objectives. Ideal sets of capabilities must become

[6] This article's lead-author was a member of NN+ staff throughout the duration of the Partnership Programme. This afforded further insight into the formation and operation of the programme.

a pragmatic list that can be studied and should include all important elements non-reducible to the other elements, even if there are some overlap.

Guided by these criteria we identified a list of capabilities, arrived at inductively from the literature and project documentation from within the NN+ partnership programme. In the first instance we conducted a focused literature review to find the extant literature on the practice of conducting transdisciplinary research. This review searched for peer-reviewed articles on conducting transdisciplinary research and examined them for capabilities being demonstrated.

Drawing from the project documentation such as proposals and reports, we also assessed the reported views of the researchers themselves to inform our set of expected capabilities. In proposals, researchers identified those methods and literatures which were important to the project as well as the individuals involved and their expertise.

Finally, we integrated observations from a workshop organised by the NN+ entitled 'Transdisciplinary Methods for Developing Nexus Capabilities'. This brought together researchers from across the Nexus Network as well as others with an interest or expertise in transdisciplinary research for sustainability (Ince 2015). Workshop activities yielded discussions about a number of capabilities which, for the participants, were important in addressing the needs of transdisciplinary research.[7] These capabilities are reported in aggregate in Section 4.1.

3.1.2 Stage II - Mapping capabilities at research sites

Following Step 2 in the realist evaluation procedure and guided by the heuristic in Figure 2, we gathered data on actual capabilities valued by researchers *in situ* within each case. In order to map researchers' cognitive capabilities, bibliometric profiles for each of the research projects were compiled. These consisted of aggregate records of peer-reviewed journal publications of constituent researchers. Mapping the bibliometric profiles onto Web of Science categories (Leydesdorff et al. 2013) gave us insight into the different cognitive capabilities and disciplines that constituted each of the NN+ projects[8]. Furthermore, and despite some explicit limitations,[9] for each of these project profiles, a co-authorship map gave us inference into potential relations between project researchers.

In parallel, a questionnaire was deployed to all the participants in the five NN+ projects. The questionnaire captured the nature and frequency of interpersonal interactions within and across projects in order to map further individual, collective and group capabilities. In addition to this, we also gained perspectives on how these capabilities were valued and experienced by researchers.

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[7] The workshop was organised around two generative questions: 1) What different kinds and interconnections of method in contrasting contexts, form the most practical basis for enabling transformative action to address Nexus challenges? 2) How can such encompassing Nexus methodologies best enable academic, government, business and civil society actors to develop appropriate skills, training and research capabilities?

[8] It is suitable to use WOS categories based on already done work for capabilities because capabilities are at their core prospective. We find it reasonable and plausible to use these disciplinary categories as indicators of capability, that is for what researchers can do in the future if they choose.

[9] Knowledge outputs only partially reveal characteristics of a knowledge community (Strathern 2004). More specifically, a limitation of co-authorship mapping is the reduced efficacy for early career researchers and non-academic participants (who have fewer publications). These limitations were mitigated through close analysis of the project proposals and the self-reported biographies of project researchers.

Finally, a second workshop in May 2018 convened researchers from across the NN+ Partnership Grant portfolio (Ayre & O'Donovan 2018). Participants were invited to reflect on capabilities within their projects by building their own maps of stakeholders, project participants, socio-material relations, resources and institutions (Schiffer 2007). This method was adept at capturing collective and group capabilities and associated aspects of the extra-organisational and institutional milieu. Participants were also asked to respond to representations of the bibliometric profiles, providing important feedback on the patterns and gaps in that data.

Data from these methods formed the basis for 15 semi-structured interviews with project researchers from across the five NN+ projects. These interviews had two objectives: first, providing further feedback loops within the evaluation framework. Second, capturing research practices and capability experiences that were important to researchers actually doing the research.

3.1.3 Stage III - Comparing the list of expected capabilities with evidence from research projects

The final step of realist evaluation is, in practice, multiple iterations of the same step – an evaluation is a cyclical recursion between the IPT and the data (Gilmore et al. 2019). The point is to iteratively reflect upon our initial list of capabilities as our data collection and analysis evolves. This meant that the initial list of expected capabilities was continually compared to the capabilities that we mapped in the cases. This interplay between expectations and reported reality is where realist evaluation highlights those aspects which are structural, unexpected or absent entirely.

In the recursion between data analysis and the IPT, we constructed narratives of each case. These drew upon the final reports of each project, the incoming interviews, questionnaires, and bibliometric data, and the outputs of the 2018 workshop. These stories provided us with an understanding of how each project practiced transdisciplinary research and gave us a basis for comparison. As more data was gathered, these stories became thicker, more detailed, and increased in specificity. This allowed us to infer the capabilities valued by researchers within each project.

Constraints of space preclude the presentation of detailed case narratives for each of the five NN+ portfolio projects. However, given the goal of the paper is to present and justify the evaluation framework, the combination of an embedded paradigmatic case (Flyvbjerg 2006 p. 232), alongside supporting data in Section 4.3 is sufficient to support the claims made in Section 5 and the conclusions offered.

4. Results

4.1 Reporting an inductively built list of capabilities for transdisciplinary research

Our first analytic stage was to identify empirically the capabilities claimed to arise within the unit of analysis, the transdisciplinary research project. Following the procedure described in Section 3.2, our research identified the list of transdisciplinary capabilities presented in Table 2.

Table 2. Inductively generated list[10] of capabilities for transdisciplinary sustainability research. See Appendix 2 for further elaboration and justification of these capabilities.

Capability		Heuristic location
1.	Cognitive capabilities including	
	a) *A cognitive capability to perform research across disciplinary boundaries*	Cognitive capability
	b) *A cognitive capability to apply tools and frameworks in new situations*	Cognitive capability
	c) *A cognitive capability for a sustained appreciation for the importance of the particular*	Cognitive capability
2.	A capability of pluralism	Individual capability
3.	A capability to acknowledge and communicate complexity	Individual capability
4.	A capability for reflexivity	Individual and collective capability
5.	The capability to actively and critically interact with and challenge power	Individual and collective capability
6.	The capability to sustain a livelihood	Individual capability
7.	Capabilities to manage a research team	Individual and collective capability
8.	Capability to trust in collaboration	Individual capability
9.	A capability to be egalitarian	Collective capability
10.	A capability to be humble	Individual capability
11.	The capability to build societal capacity for democratic struggle	Collective capability

With reference to this list, Sections 4.2 and 4.3 map and qualitatively describe capabilities found in the NN+ project portfolio. Section 4.2 reports a narrative analysis of a single project while section 4.3 assesses capabilities across the whole NN+ portfolio.

4.2 Mapping the capabilities within a single NN+ Partnership Programme project. A research narrative from Project 1

Our second analytical stage was to assess whether and how actual researchers in different NN+ research projects value and experience these capabilities. We illustrate the method though an embedded case-study, reporting the case narrative for Project 1 in the NN+ Networking Programme, with reference to capabilities from Table 2 in parentheses.

The aim of Project 1 was to facilitate the transfer of research findings from environmental social sciences into the UK policy context[11]. Bibliometric analysis shows the aggregate set of researchers' cognitive capabilities (Table 2; capability 1) included capabilities from geography and other social sciences with environmental sciences and civil engineering, illustrated in Figure 4. The analysis highlights the role of social science capabilities required to underpin the project. These are indicated by the large clusters of geography and social science on the left-hand side of the map. This is in line with the ESRC's explicit

[10] The capabilities list was generated from source materials outlined in Sections 3.2.1 and 3.2.2. These include academic literature, a working paper commissioned by the NN+ (Stirling 2015), close analysis of NN+ project reports and two workshops.

[11] For summaries of all NN+ projects, see Appendix 1

goal for the NN+ to "engage the social science community with these complex 'Nexus challenges' and link them to research users from business, government and civil society" (UKRI 2020).

The presence of large clusters on the right-hand side of the figure shows that project team also included researchers with published outputs in the natural and environmental sciences and engineering, clustered further away from the dominant social science disciplines indicating a plurality of cognitive capabilities. Moreover, qualitative data revealed the presence of collective capabilities in the team that made the translation, integration and operationalisation of these diverse capabilities possible (2, 4, 7). These included capabilities to allow reflection on past collaborations where were required to effectively translate social science perspectives to practitioner partners in water, energy and food industries.

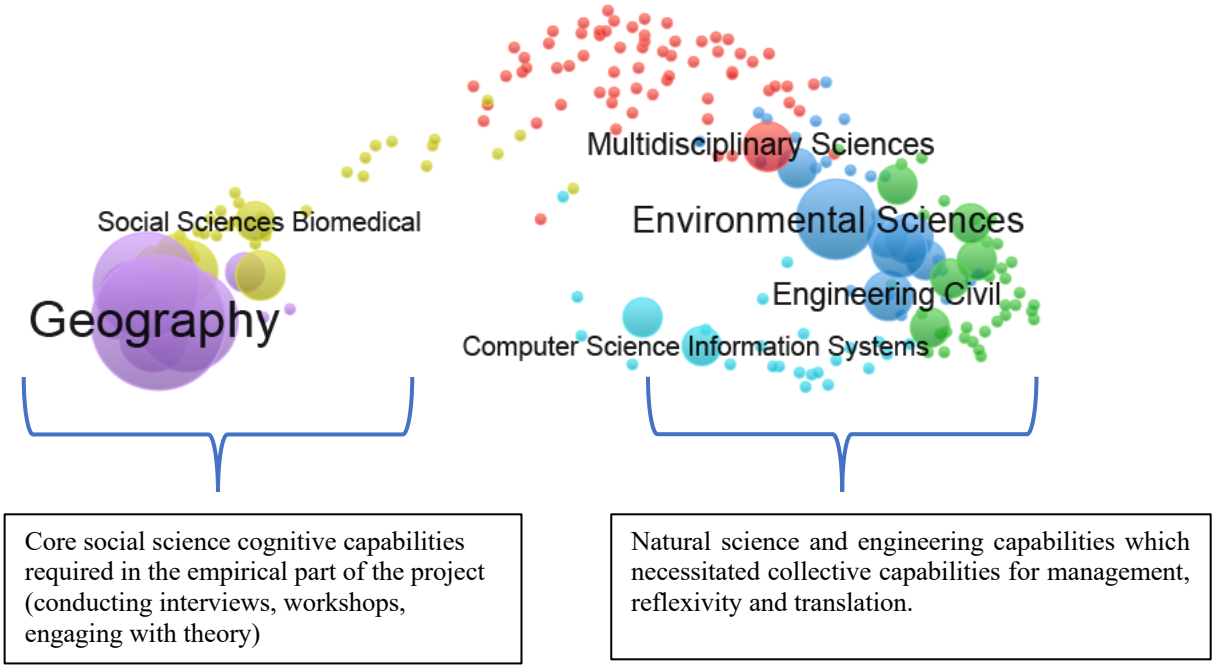

Figure 4. Cognitive capabilities for researchers in Project 1, mapped onto the Web of Science (WoS) Map of Science (Leydesdorff et al. 2013). Each node represents a WoS category, in sum indicating the aggregate of researchers' cognitive capabilities within the project. Clusters of cognate disciplines are based on citation flows in the overall WoS corpus and are represented by nodes sharing the same colour. The two dominant clusters in the figure indicate the research team is constitutive of capabilities from geography and social sciences on the left with environmental sciences and civil engineering on the right. These have been augmented to show where group and cognitive capabilities exist.

Despite this diversity of capabilities, the majority of project researchers were interpretive social scientists with a shared research interest in the domestic use of water, energy and food. This led to a perception amongst the researchers that the integration of academic disciplines was less significant than extra-institutional collaboration with practitioners:

"Insofar as our project was transdisciplinary, it was transdisciplinary in terms of involving practitioners as well as academics. Personally, the term I would use would probably be 'collaborative research' because it was collaborating with practitioners" (Project 1 researcher).

It is curious that despite this evidence of cognitive capabilities to perform research across disciplinary boundaries, disciplinary integration is underplayed by the researchers on the project. One reason for this is the project did not collect novel empirical data in the domains of environmental science and

engineering. Yet several members including one senior co-investigator have collaborated with engineers and physical scientists for over 10 years. This is important because the decade of interdisciplinary collaborations, evident in co-authorship analysis (see Figure 5), laid the ground for trustworthy collaborations and effective communication of complexity surrounding environmental science and policy (3, 8).

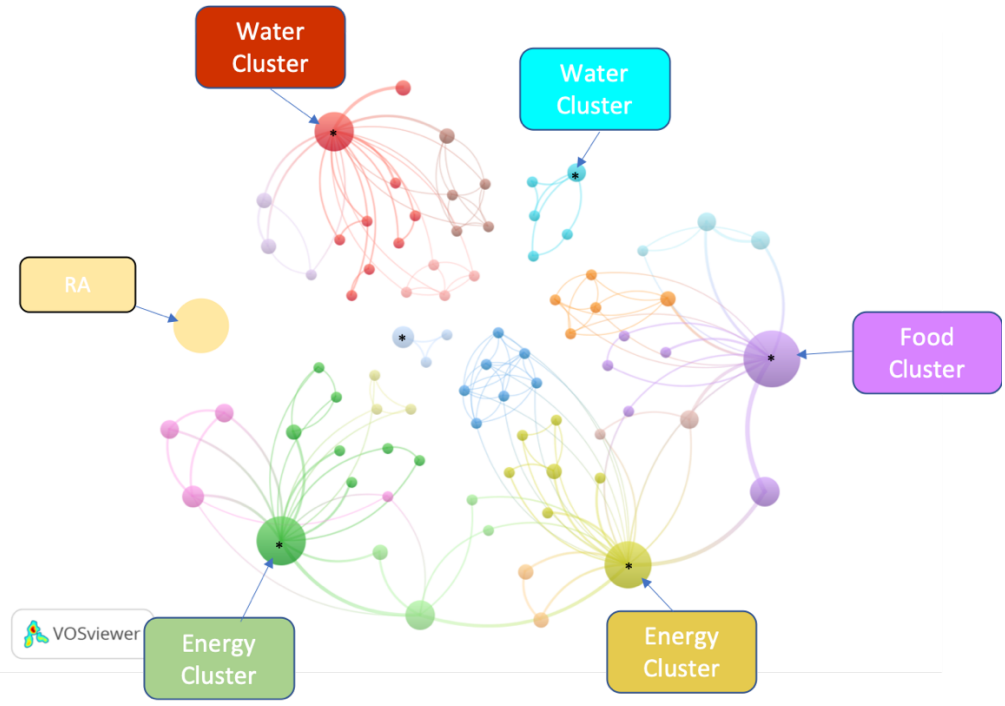

Figure 5. An augmented co-authorship graph for Project 1 which illustrates nexus-domain expertise in water, energy and food, and highlights 'missing' cognitive capabilities of early career researchers, represented by the yellow research associate (RA) circle. Nodes represent individual authors in the network. Links represent a co-authoring relationship. Clusters of authors mapped using VOSViewer's clustering algorithm. Authors that were in the project are identified with an asterisk. The early career research associate is indicated by 'RA – research associate'. These have been augmented to indicate where group and cognitive capabilities exist. (Note: co-authorship links are best observed on online version of article)

Mapping capabilities reveals not only what cognitive capabilities were cultivated, but indicates how. Researchers engaged with the technical and scientific aspects of water, energy and food demonstrated capabilities of humility and pluralism (2, 10):

"It's very easy to have a critical or a meta orientation towards science if you were versed in rudimentary sociology. I don't think that does you much good. (…) economists or scientists may have models of human action that we find objectionable as social scientists. Rather than going, "Okay, well they're stupid, let's dismiss it," they're not stupid. Have the courtesy to understand what it is that other people do." (Project 1 researcher)

Furthermore, researchers praised the egalitarian ethos in the team (9), demonstrated through collaborative approaches to writing:

> *"I don't think there was a particular hierarchy between us. I would come up with the same copy, and depending on colleagues' availability, would do the rounds between them. It would come back to me with the edges smoothed and some suggestions for further work to do. Generally, chopped. I felt like it was a nice mix" (Project 1 research associate)*

It is not just knowing one-another but working and publishing together that is particularly generative of collective capability building in this regard, again illustrated in Figure 5. The bottom right corner of the network illustrates what one interviewee called a "*disciplinary North-West hub*", referring to the region of England in which their co-authors worked. These researchers write together to advance social theory, even though their expertise is located in various domains of the water-energy-food nexus. In contrast, a different co-investigator (represented by the isolated set of predominantly red nodes and connections at the top of the graph, is distant from the network's dominant part - this researcher's publications are mostly collaborations with engineers. These networks indicate not only existing cross-disciplinary capabilities, but different kinds of cognitive, individual and collective capabilities.

Interviews with researchers revealed the pre-existence of academic and academic-practitioner networks (labelled clusters, Figure 5) which allowed researchers build their project team at short notice and then manage the group through the consecutive rounds of NN+ funding:

"Longstanding links between our two universities is the bottom line. We know each other personally; we tend to work in the same sort of field"

"[…] It's a completely pre-existing academic and stakeholder network, which is handy to have when you've got to turn around a proposal in a tight timeframe. So, you know, if you've got a proto-team already in place you can mobilise it quickly in response to things" (Project 1 researcher).

Summarising, the narrative shows researchers understood the project as an application of policy orientated social science tools in new situations. Within the project, researchers cultivated group capabilities to be humble, plural, egalitarian and reflexive. In particular, our analysis revealed the value of professional networks within academia and with practitioners. While interviewees notably did not emphasise cross-disciplinary cognitive capabilities, capabilities that allowed them transgress institutional boundaries were valued. Also valued were capabilities that allowed them manage the project team, communicate complexity across nexus domains and sustain their livelihood through each round of competitive funding.

4.3. Capability mapping across the NN+ Partnership Programme

So what capabilities are evident when we look across the portfolio? In this section we relate our third analytical stage where we report the evidence, we find for capabilities following the heuristic (Figure 2). We note a number of patterns arising from common configurations of researchers, knowledge and research project resources. While the particulars of each of the five projects in the NN+ portfolio varied, systematic mapping of cognitive capabilities and sustained focus on other capabilities revealed rich insights.

4.3.1 Individual capabilities: engaging with power structures

Across five project teams, a diversity of participant perspectives was evident. Despite this diversity, there are some common ways in which capabilities are valued and experienced. One way in which interviewees conceptualised capabilities was by talking about what capabilities they valued in co-workers. These included capabilities of humility (Table 2, capability 10), in colleagues who "*[don't] think somewhere in the back of their minds that they are superior"* (researcher P4); capabilities of pluralism (2) in colleagues who are "*not particularly holding to any Western way of understanding the data*" (researcher P3); and capabilities to be egalitarian (9), in colleagues who can *"(…) learn to listen what the stakeholders need and understand how you can respond to their needs, and not just the*

project's" (researcher P1). In other words, a researcher who strives to identify, engage with or alter existing research priorities power structures (5).

This evidence shows that these researchers value being able to break down the hierarchies traditionally constituted by academic disciplines, social status, seniority and uneven geographies – even if they are not always able to achieve this. A researcher in Project 4 said:

"a lot of the funding is directed through the [global north] universities, so although we were able to give our partners money through subcontracts, we were still controlling it. So, in a sense there is some kind of implicit hierarchy that goes with it. (…) Are there ways in which we could support research partners in the global south more directly?".

The point here is that capabilities that might offer better support to overseas colleagues were absent, or structural impediments were too strong to overcome.

4.3.2 Collective capabilities: the value of project networks

Capabilities are also influenced by the configuration of people, knowledge and resources within research sites. Throughout the portfolio, capabilities like egalitarianism, team management and trust in collaborations (7, 8, 9) were experienced through practices such as "*encouraging to ask silly questions*" (researcher P2); "*not being precious during collaborative writing*" (researcher P1); and "*managing tensions with respect and positivity*" (practitioner P5). It seems that not only are these capabilities individually held, they are cultivated through shared concerns and interests.

Furthermore, interview data suggest that networks provide positive feedback for researchers, strengthening capabilities to conduct transdisciplinary research*:*

> *"I guess these things have a life of their own. Once you start engaging people and you find people you like and can work with, then you want to do more" (researcher P2).*

We identified an example of such a network in Project 1, but such networks can be established in numerous ways, by primary investigators opening access to historic networks (P1 and P3), through networking grants (P1 and P2) or conferences (P4 and P5). Project networks (see Appendix 2) demonstrate the critical importance of nurturing connections over time. Participants reflected that without pre-established personal networks it is challenging to sustain collaborations once the project finishes. This was the experience of the investigators in P4 and P5, where the connections between the researchers and practitioners were established only shortly before the project start and through professional events rather than personal networks:

"It's very hard to keep networks running after a project has ended. With all the other drawings on our time, other things tend to take priority, especially then if they're to do with the lifeblood of running an institute i.e. income streams" (researcher P5).

4.3.3 The influence of extra organisational and institutional milieu: a need for transdisciplinary research policy

Participants repeatedly pointed out the need to enhance capability building at the institutional level. Training in transdisciplinary practices, more flexible procedures for bidding for research funding, provision of career progression mitigating risk for those engaged in transdisciplinary research (6), and investment in cross-institutional networks are all crucial enablers for transdisciplinary research

mentioned throughout our interviews and questionnaires. They facilitate the cultivation of cognitive capabilities as well as those that enhance livelihood, pluralism and capabilities to challenge-power. When asked about the existing capabilities for transdisciplinary research at the university and research council levels, all participants emphasised the lack of appropriate structures and policies.

Participants perceived transdisciplinary research as a risk to the academics and stakeholders, who, without the institutional support to build long term-partnerships and secure careers, are left to the project-based and precarious working conditions. Similarly, under the current research evaluation framework, transdisciplinarity was seen as a risky endeavour for the universities, which often retreat to mono-disciplinary research and commercial partnerships as they are easier to prove impactful and lucrative according to a researcher P4:

"[The Research Excellence Framework] is still siloed. When you put together projects and publications, PI's and Co-I's and are becoming increasingly pickier as to what publications they are putting together, what sorts of projects. Publications can tick boxes. Sometimes they can be put in a tick box for engineering, sometimes for geography. I think REF conflates the whole transdisciplinary agenda because it's still very much siloed.".

Frustrations about the lack of support for capabilities to sustain a livelihood from transdisciplinary research was put even more succinctly by this researcher from Project 1:

> *"if these grand challenges are so bloody important, then how do we invest in people's careers that are also transdisciplinary without increasing precarity and casualisation?".*

In summary, mapping capabilities through each of the heuristic levels we found a plurality of capabilities that are valued and experienced and some that appear in Table 2 that are absent entirely. In the following section we discuss some points particularly salient for the provision of policy in these areas.

5. Discussion

5.1 Convening cognitive capabilities for transdisciplinary research

At a programme level, the Nexus Network+ appears to have achieved its goal. The network convened a host of cognitive capabilities, anchored in social science disciplines, in a problem domain that was and is predominantly natural and systems science led. At first glance, this represents a significant achievement for the Network, and their funders, the ESRC, whose explicit mission was to pump-prime social science capacity and capabilities in WEF Nexus domains. By convening a portfolio of projects that clearly were constitutive of plural cognitive capabilities, the NN+ extended a systems sciences version of nexus and put social science firmly on the playing field. If we take diversity in knowledge production seriously, then this development would seem to be a welcome one.

Yet, using a capability approach within our realist evaluation framework, we have revealed a more ambiguous picture. We have shown how a plural set of cognitive capabilities (social and natural sciences and other knowledge) are available to research teams and valued. These results support prior concepts in STS that it is not simply the presence of disciplinary knowledge, but the relations between them, and their situation within a project group that are important in transdisciplinary research for sustainability.

The value of the capability approach here is in its ability to interrogate this aggregate perspective. All projects, at least on paper, convened diverse sets of cognitive capabilities. But individually, projects self-reported varying degrees of success. This research shows that simply bringing together groups of researchers with the requisite cognitive skills is not sufficient for practicing transdisciplinary research. We provide commentary on notable aspects of these findings and offer speculative strategies of support and mitigation below.

5.2 Cultivating transgressive capabilities and accounting for their absence

Notable in interviews and questionnaire data are a set of motivations, research practices and underlying capabilities specifically required to transgress institutional settings and boundaries. These have a number of characteristics in common. There is a shared motivation for broadening out the inputs of research participants and opening up the outputs to a greater number of actors. We see the creation of new forms of expertise. And we find that researchers are motivated to confront incumbent knowledge gatekeepers and so to challenge power and indeed *give away power* to non-academic partners.

These capabilities challenge traditional modes of research, by transgressing disciplinary lines and institutional boundaries and broadening out who it is that gets to produce knowledge. In this regard, these activities are in opposition to an orthodox model of a research-performed-by-expert, whose professional disinterestedness grants them a monopoly on truth (Nowotny 2003). These capabilities are similar to what Nowotny calls 'transgressive competences' (2000). That is, the collective capability of experts to come together transgress the boundaries of disciplinary knowledge and the constraints of their own individual limits of knowledge (Klein 2010). These then represent a set of transgressive capabilities that explicitly call into question power in knowledge production.

We find compelling evidence for these 'transgressive capabilities' throughout the programme, both in their successful cultivation, and in their noted absence. In practice, researchers cultivated and mobilised these capabilities through their involvement in multi-institutional networks, by enrolling non-academic actors into research projects, and maintaining relations with actors over time. Two of five projects showed evidence of significant transgressive capabilities (P1 and P3) with two more projects (P2 and P4) showing evidence of some transgressive capabilities. The primary investigator in Project 4 for example was conscious of power imbalances between the UK team and the overseas partners, but in practice found it very difficult to support capability development of overseas partners from the UK side. In comparison, researchers in Project 3 had spent over a decade building up these kinds of capabilities through the establishment of new networks of local people.

5.2.1 Absences of expected and valued capabilities

All projects convened a plurality of cognitive capabilities to satisfy the programme's requirements. Yet, despite our inductive list of transdisciplinary capabilities being recognised and valued by individual researchers across the portfolio, transgressive capabilities were unevenly distributed through the five projects, and in one, P5, effectively absent. Capabilities that might have allowed the PI of Project 4 better support their overseas colleagues (for example by strengthening capabilities 6 and 7) were either absent, or structural impediments were too strong to overcome. Moreover, due to the lack of the pre-existing networks, the researcher of Project 5 noted the absence of capabilities that would allow them transgress disciplinary and institutional divides (for example Table 2, Capability 8) – crucial in working with non-academic partners.

Researchers indicated some reasons for these absences including insufficient funding for establishing and maintaining new networks; asynchronous working relations with powerful practitioners, which limit researchers' ability to challenge power; lack of career trajectories for transdisciplinary researchers; bidding procedures which prevent meaningful input in research design from non-academic collaborators; a UK research evaluation framework which is perceived as siloed along disciplinary lines.

5.3 Maintaining a backstage capability space for transdisciplinary research

Where transdisciplinary capabilities have been well-cultivated, in P1 and P3 and to a lesser extent P2, these capabilities have been supported by long-established networks of actors, knowledge, relations and other capabilities. Capability development has taken place through other means, that is, outside of the project boundaries established through the NN+ Partnership Programme. In these cases, we find evidence of capability building over a multi-project timeframe initiated prior to the NN+ Programme. In the case of Project 3 for example, this 'backstage' capability space, was established by researchers over the course of a decade by building up networks and maintaining relations and the provision of new resources such as funding and researchers.

This has implications for our understanding of the development of research capabilities and broader capacity. The requirement for the cultivation of capabilities is well understood by researchers and funders – this was clearly communicated following RELU (Lyall et al. 2015) – and it was made explicit in the overall aims of the NN+. These aims mirror trends in the UK and elsewhere by framing urgent societal challenges and instigating pump-priming research in these areas so as to expand capacity for further research. However, what is less evident is an awareness of and requirement to assess spaces where these capabilities might be maintained. The risk here is that of a significant Mathew effect where advantage accrues to already established powerful research players and networks consolidating resources. This has negative implications for diversity of knowledge producers.

A second issue arises with the risk of evaluations systematically over-determining success or failure based on more visible cognitive capabilities, thus further privileging incumbent research approaches to the detriment of transgressive capabilities in the making. In other words, the contribution of the cultivation and deployment of transdisciplinary and specifically transgressive capabilities to good research is in danger of being under-specified in post-hoc assessment to the advantage of capability maintenance elsewhere.

Regardless of these risks, opening-up backstage capability spaces to evaluation is an important task in addressing a recurring comment on the difficulty of establishing and maintaining transdisciplinary research practices – that of insufficient time. Quite simply, it takes a long time to establish the socio-material conditions - the people, knowledge, relations and resources - to *do* transdisciplinary research. It seems that in the 12-month time frame for these five projects, there was a great impact on the maintenance of transdisciplinary capabilities in already existing backstage capability spaces (P1, P3), rather than on the successful cultivation of new capabilities (P5). So, while we could regard this maintenance as a positive outcome, the difficultly of cultivation indicates a deficiency in the pump-priming model employed. Despite successfully convening a plurality of cognitive capabilities, the pump-priming goal of cultivating novel capabilities is less clearly met. It seems that while old pumps were being maintained, the task of readying new pumps met with less success.

Of course, it should be noted that the distinction between modes of convening, cultivating and maintaining capabilities is not entirely clear-cut. In convening cognitive capabilities, and configuring

people and knowledge in new projects, it would be surprising if at the very least some new capabilities were not cultivated. To be clear then, the contribution we make here is to show that the foregrounding of these modes of capability development in different ways, whether it be in bid-selection or project evaluation, has consequences. It is the job of future research to explore these consequences further. The capability approach may be of more use here, offering conceptual tools, for example, that might usefully distinguish capabilities from functionings, and conversion factors (illustrated in Figure 1).

6. Conclusions

This paper has proposed a novel framework that can test how projects develop capabilities for transdisciplinary research. We applied this framework to evaluate capabilities for transdisciplinary 'nexus research'. Our main empirical finding is that under a 'nexus research' framing, the NN+ Partnership Programme convened a diversity of cognitive capabilities. However, these capabilities on their own were insufficient to support transdisciplinary research. We noted two other modes of capability development in the research projects we evaluated. The cultivation of transgressive capabilities and the maintenance of a long-standing capability space required for transdisciplinary research.

This research has important implications for developing capabilities and expanding the capacity of research systems for transdisciplinary research. The basis of legitimacy and accountability in transdisciplinary research is not endogenously derived, but emanates from practices of knowledge production which are transgressive, inclusive, and societally distributed. One important observation from this research is to show that developing better expertise for real word problem solving (be they framed as grand challenges, societal missions or agendas more modestly named) is not about assembling the best experts from a rage of narrow academic domains. Rather, it is about fostering transgressive capabilities that will contribute to knowledge production that gains legitimacy and accountability from the plurality of contributing actors, the wider societal contexts in which it is produced, and interconnected relations between these actor and contexts. We have contributed a set of methods that can evaluate these practices and procedures.

The current funding system in the UK treats research capacity as held in disembodied projects that may be turned on and off as demand dictates (Vaesen & Katzav 2017). This is simply not the case. Our evaluatory approach facilitates a more nuanced understanding of what is going on and the extent to which capabilities are being convened, cultivated, or maintained under a buzzword like *nexus*, or indeed *sustainability*. This has implications and applications in particular for how research is organised to address emerging hot topics.

The Capability Approach employed here to evaluate research capabilities demonstrated both their importance and their absence in traditional research evaluation frameworks. As our own bibliometric analysis shows, using downstream outputs as a measure of capacity-building outcomes limits the scope of the kinds of capabilities which can be measured. By expanding the scope of our inquiry beyond outputs to the inner workings of the project, we show how an evaluation of capability-building must acknowledge the epistemic and social contexts of knowledge production. This is mirrored by other recent additions to the research evaluation toolkit (Bone et al. 2019). The key point in both approaches is opening the black box of research projects to explore knowledge production downstream of traditional indicators. Future research might explore complementarities between these approaches.

This has practical implications for the evaluation of research. The framework proposed here may be taken as one useful component in a broader evaluation of the processes and impacts of transdisciplinary work (Huutoniemi 2010). Our framework has particular salience for funders interested in fostering long-term capacity-building. Evaluations that take into account capabilities rather than more instrumental research outputs offer benefits. By foregrounding capabilities – the possibilities for research practice valued by, and available to, researchers – evaluation is focused exactly at the point where the *broadening-out* of research inputs to a wider range of actors and knowledge might be most useful (Stirling 2008, 2015). This is important if we are to take transgressive capabilities seriously. Moreover, our framework affords an understanding of how capabilities are situated and contingent on real-world contexts, and may be combined and cultivated within the messy socio-material and institutional milieu of knowledge production. Future work might make further use of the conceptual tools offered by the Capability Approach to explore in greater detail the mechanics of how capabilities are influenced by available resources such as knowledge and people and the socio-material situation.

We believe these findings to have particular salience in pump priming instruments such as sandpits and UKRI Network+ model where the urgency of developing capabilities to research societal issues are stressed yet uncertainties regarding the most appropriate action remains. Contemporary examples in US, European and UK research policy systems include climate change, artificial intelligence, and economic productivity. The cultivation and maintenance of transgressive capabilities in cases like these is a prudent way in which funders might plan for such urgencies, the details of which are often difficult to anticipate. Crucial to transdisciplinary methods, and in particular transgressive capabilities identified in this study, is the affordance of time to pause and reflect. Such capabilities will augment research system capacity only if well-prepared in advance. Our evaluatory framework can contribute to identifying, cultivating and maintaining such capabilities.

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Conflicts of interest

The authors report no conflicts of interest.

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Supplementary data

Appendix 1 – Summaries of Nexus Network+ projects and bibliographic mapping

Project 1 – Transdisciplinary collaborations within a UK region

About the project: This project aimed to engage policy makers with the social sciences' theories on sustainable kitchen practices. In this project we note diversity of cognitive capabilities is underpinned with evidence of strong cognitive links between researchers. This has been built up over a long timeframe.

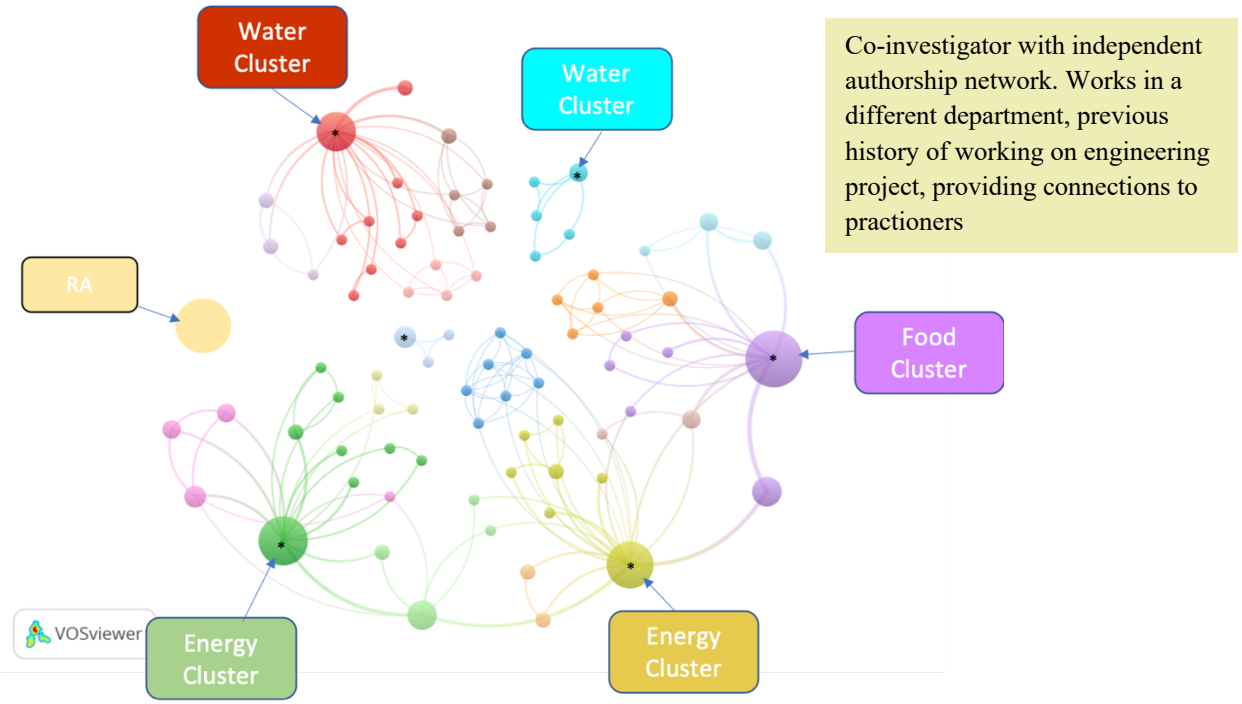

Figure A1. An augmented co-authorship graph for Project 1 which illustrates nexus-domain expertise in water, energy and food, and highlights 'missing' cognitive capabilities of early career researchers, represented by the yellow research associate (RA) circle. Nodes represent individual authors in the network. Links represent a co-authoring relationship. Clusters of authors mapped using VOSViewer's clustering algorithm. Authors that were in the project are identified with an asterisk. The early career research associate is indicated by 'RA – research associate'. These have been augmented to indicate where group and cognitive capabilities exist.

Project 2 – UK–overseas project collaboration

About the project: The project combined economic and soil science analysis to aid farmers' decision making.In this project the primary investigator enacts a strong individual leadership role in aligning people and their capabilities. This was reinforced by concurrent activities mobilised by another non-NN+ project run over a similar timeframe. Nevertheless, larger ambitions had to scale down due to delays caused by the complexity of administrating research activities overseas.

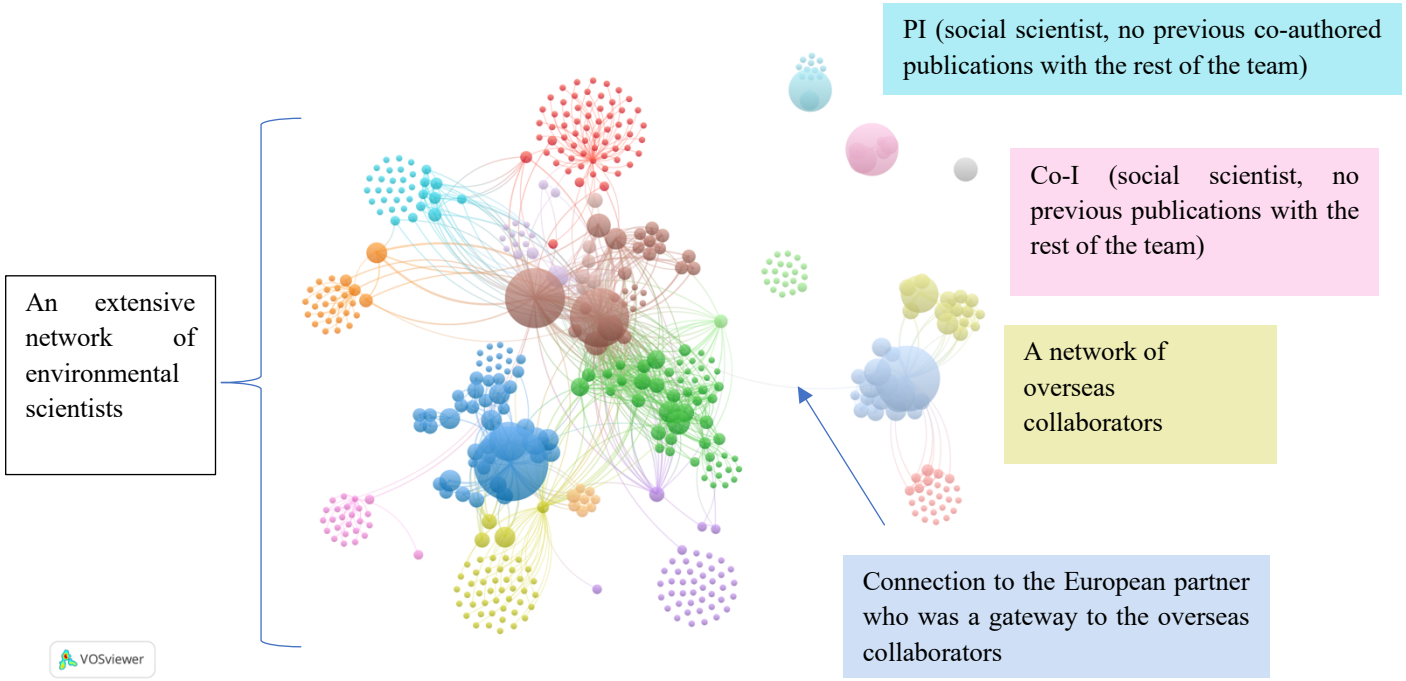

Figure A2. An augmented co-authorship graph for Project 2 following protocol of Figure A1.

Project 3 UK-overseas project collaboration

About the project: The project aimed to collect a diverse array of natural science data from an overseas region and integrate them into the already existing social science database of the area. The project engaged with the local policy makers and community members during data collection and outreach. The primary investigator played a convening role and was not involved day to day. The UK based research group had already funded a PhD researcher at an overseas partner research organisation indicative of, and constitutive of a long-established trans-national research network. Difficult to ascertain where the power lay between partners.

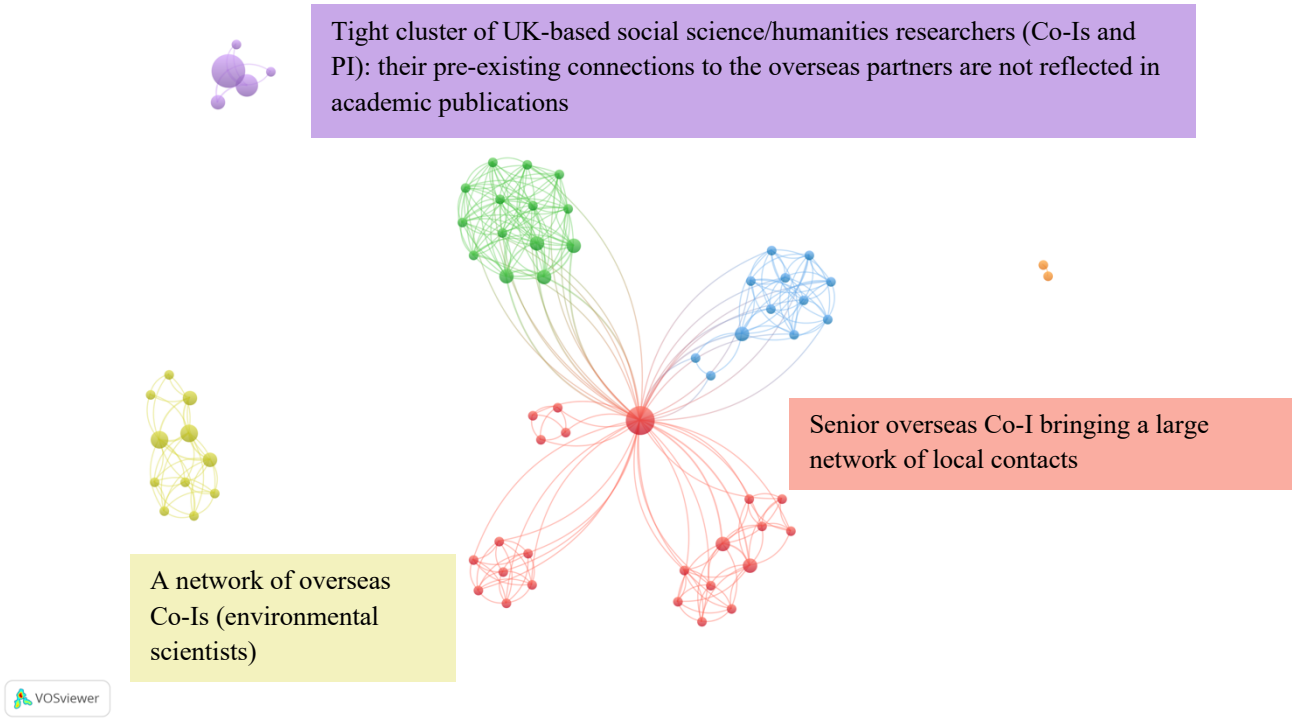

Figure A3. An augmented co-authorship graph for Project 3

Project 4 - UK-overseas project collaboration

This project gathered qualitative insights on energy production, consumption and related sustainability dilemma. In this project, cognitive capabilities related to interpretive research techniques existed within the UK academic team but were not uniformly matched in the field. The funding itself did not allow for training. Capabilities did not exist to easily connect UK and overseas academic structures creating delays and other barriers to getting work done.

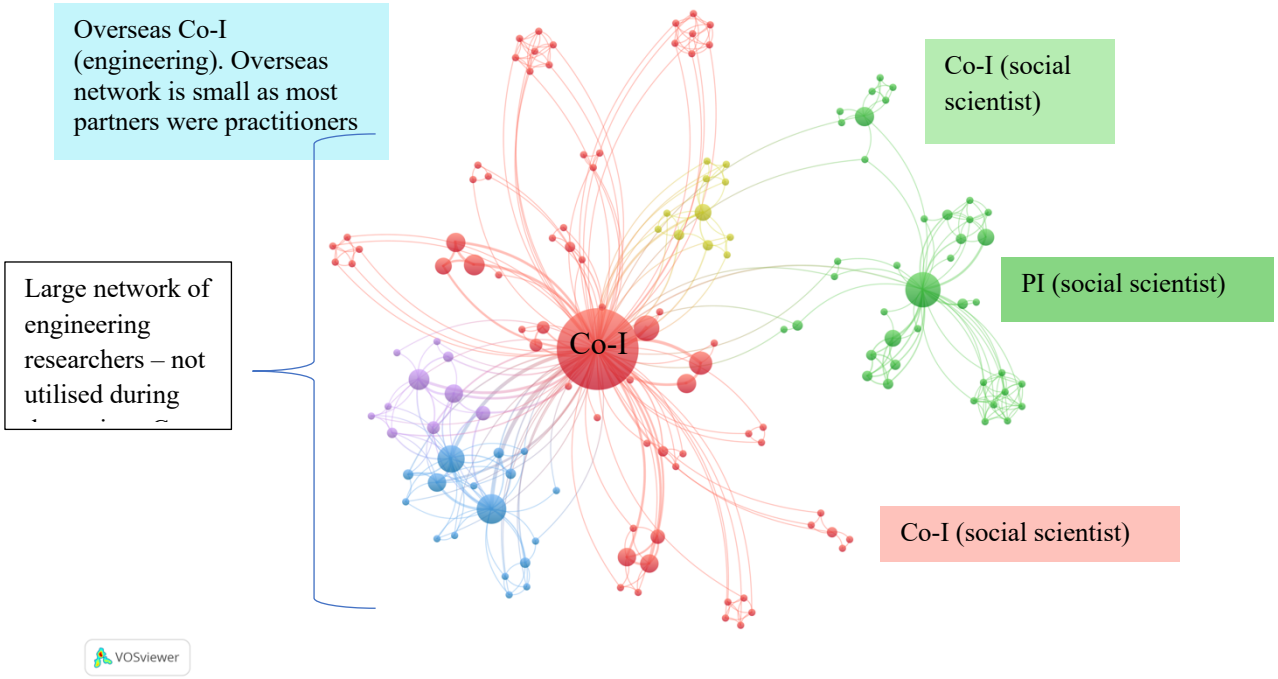

Figure A4. An augmented co-authorship graph for Project 4 following protocol of Figure A1.

Project 5 - Transdisciplinary collaborations within a UK region

The project developed a series of deliberations on the future scenarios related to sustainable food systems. In this project the primary investigator played a convening role initially and was not involved in day-to-day activities of the project. The researchers did not have pre-existing connections with the practitioners participating the in the project. The short-term nature of the NN+ funding did not allow to create a community of practice which would last beyond the timescales of data collection and dissemination.

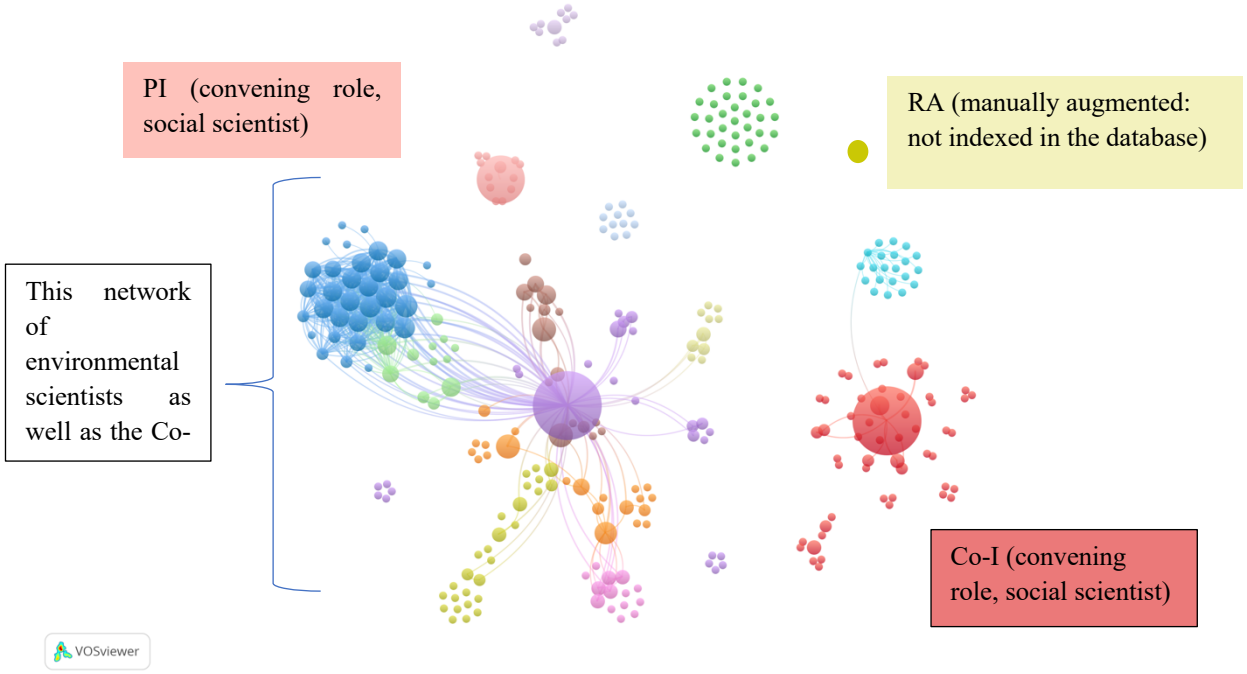

Figure A5. An augmented co-authorship graph for Project 5 following protocol of Figure A1.

Appendix 2 – Transdisciplinary capabilities

Table A1. Inductively generated list of capabilities for transdisciplinary sustainability research

Capability		Elaboration and justification
C1.	Cognitive capabilities	These are the specific scientific and technical knowledges and skills required to 'do' research and 'be' a researcher. Expertise in a 'home' discipline is particularly valued. Three aspects of cognitive capabilities are important in the context of nexus sustainability research. (Heuristic: cognitive/individual capabilities).
	a) A cognitive capability to perform research across disciplinary boundaries	The capability to do research beyond the boundary of the home discipline. While other capabilities below are about working with other people, this capability is about having available the cognitive ability to use or learn new ways of doing and knowing research.
	b) A cognitive capability to apply tools and frameworks in new situations	Addressing sustainability challenges, methodological tools can in principle be readily transferred across otherwise quite different kinds of methods. Examples include techniques for handling probabilities, taxonomies, text documents, geographical data or a host of more mathematical procedures like sensitivity analysis, time discounting scoring and weighting. In the case of nexus-research, key settings may involve radically different kinds of organisations, procedures, stakeholders, power relations, purposes or wider political-cultural context. These might include international assessments, government enquiries, regulatory committees, participatory processes, NGO studies or social movement activities and accessing data in firms.
	c) A cognitive capability for a sustained appreciation for the importance of the particular	This is an important capability when explicitly investigating interconnections between nexus domains such as water, energy, food and the environment. This capability fosters caution over the implications of generalisation.
C2.	A capability of pluralism	Capability to be ontologically and epistemologically flexible, (to accept different levels of reality, openness to other views. It means a capability to express and respond to scepticism, without interpreting this as existential denial. By encouraging (rather than suppressing) critical discourse, this helps foster more robust knowledge. It is important that this capability is available at all stages of research, so social science or non-academic perspectives are not merely limited to circumscribed parts of the projects. (Heuristic: individual capability)
C3.	A capability to acknowledge and communicate complexity	This is the capability to resist the closing down of plural framings via either quantitative or qualitative approaches, for example, those that might arrive at one single narrative. This also calls for capacity-building among companies, public bodies and other organisations about recognising and dealing with complex knowledge. (Heuristic: individual capability)
C4.	A capability for reflexivity	Reflexivity is the ability to reflect on how things look different depending on how they are viewed. Practically, it is the ability to discuss and consider power relations in knowledge. The capability to jointly reflect on the research topic with extra-institutional actors are considered essential to increase scientists' understanding of complex knowledge-related problems such as nexus framed challenges. (Heuristic: individual and collective capability)
C5.	The capability to actively and critically interact with and challenge power	Nexus-focused research and appraisal should orient actively towards a diversity of interests. Rather than disproportionately addressing the agendas of the most privileged 'users', neutrality means deliberately countering this bias towards the most vocal and powerful. Here, academic independence is not a transcendent virtue conferred by privilege, but a distributed emergent condition of plurality, always accountable to the particular diversities in which it is grounded. (Heuristic: individual and collective capability)
C6.	The capability to sustain a livelihood	The capability to maintain career prospects and progression based on transdisciplinary research. (Heuristic: individual capability)

Capabilities for transdisciplinary research

C7.	Capabilities to manage a research team (organisational)	Include a range of management, facilitation, administrative and trust building skills and attributes necessary in organised research. (Heuristic: individual and collective capability)
C8.	Capability to trust in collaboration	The capability to mutually learn and establish trust between researchers and other project members. Furthermore, to build team sensibilities and cultures across people with different backgrounds. (Heuristic: individual capability)
C9.	A capability to be egalitarian	Capabilities of egalitarianism foster equitable participation between researchers and in particular between academic and lay participants. These are important for non-academic stakeholders to contribute to setting research questions, methods and data analysis. For example, to co-define research questions and adapt project design with local participants. (Heuristic: collective capability)
C10.	A capability to be humble	A capability of humility requires the building of capabilities among those institutions and disciplines benefiting from established structures of privilege in, for example, nexus-related appraisal, enabling them to be more deliberate in creating spaces for others – not denying contrasting understandings as 'irrationality', 'ignorance'' or 'jargon' This means a readiness to be led by agendas or questions set outside a particular home discipline or beyond academic disciplines entirely. (Heuristic: individual capability)
C11.	The capability to build societal capacity for democratic struggle	No transdisciplinary, sustainability, or nexus-related capabilities are sufficient to substitute a fundamental overarching imperative for wider democracy. (Heuristic: collective capability)

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