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ORIGINAL ARTICLE

Enabling spaces for bridging scales: scanning solutions for interdisciplinary human-environment research

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Abstract

To tackle the twenty-first-century challenges for sustainability, a deeper understanding of their complexity is needed. Hence, interdisciplinary human–environment research integrating knowledge, perspectives, and solutions across scales is crucial. Yet, questions of 'scale' and 'scaling' continue to challenge human–environment research. Despite substantial scholarly attention to scales, no unified definitions and understanding exist, causing confusion among researchers. In this paper, we aim to provide clarity to the challenges and potential solutions to bridging scales in interdisciplinary human–environment research as well as identify leverage points and arenas of change that would enable it. We used a three-step methodology to (a) identify the challenges and solutions based on a survey of 82 interdisciplinary researchers, (b) prioritise the challenges and solutions based on expert elicitation, and (c) organise the solutions according to their potential for leveraging change at three system arenas: individual researchers, institutions and organisations, and the wider academic structures. The main challenges ranged from issues related to differences in research approaches, lack of resources for deeper collaborations, or conflicting perspectives on problem and scale definitions, to miscommunication. The specific solutions linked to these challenges were predominantly related to the potential of improving the research process through open communication, data sharing, or new techniques for upscaling or downscaling results. We argue that bridging scales requires open and humble conversations across disciplines on scale understandings as well as improved collaboration through data sharing, method development, result dissemination, and contribution to theory. Facilitating such collaboration requires enabling spaces of interaction across three systemic arenas: the individual researcher's personal commitment to open communication and reflection, the research institution's capacity to enable interdisciplinary spaces, and the wider academic system valuing and supporting interdisciplinary and cross-scale initiatives.

Keywords Scaling · Solution scanning · Social–ecological research · Sustainability · Expert elicitation

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Introduction

It is widely acknowledged that addressing the inherent complexity of today's sustainability challenges including climate change, biodiversity loss, food insecurity, and social and economic inequality requires cross-scale and interdisciplinary collaboration (Díaz-Reviriego et al. 2019; Meyfroidt et al. 2022; Singh et al. 2012). Indeed, the diverse fields of study that can be subsumed under the heading of "human–environment research" are characterised by efforts to integrate insights from the local to the global (Pereira et al. 2020; Reid 2006; Verburg et al. 2013), as well as the natural and social sciences (Fox et al. 2006; Moran and Lopez 2016; Schneidewind et al. 2016). Yet, despite substantial scholarly attention to when and how integration and collaboration across disciplinary boundaries and knowledge domains can be fruitful (Barry and Born 2013; Choi and Richards 2017; Darbellay 2015; Manson 2008; Miller et al. 2008; Reid et al. 2006), achieving cross-scale and interdisciplinary collaboration in practice continues to challenge human–environment researchers on a day-to-day basis (Cairns et al. 2020; Freeth and Caniglia 2020; Rocha et al. 2020; Villeneuve et al. 2020).

One of the particularly challenging issues related to such effort is different conceptualisations of 'scale', scale terminology, and approaches to the processes of 'scaling' data, results, and knowledge (Cash et al. 2006; Gibson et al. 2000; Manson 2008; Pulver et al. 2018). In much of the human–environment research, 'scale' is commonly used to refer to the variety of "*spatial, temporal, quantitative, or analytical dimensions used by scientists to measure and study objects and processes*" (Gibson et al. 2000, p. 219) with the term 'level' used to denote "*the units of analysis that are located at different positions on a scale*" (Cash et al. 2006, p. 2). Yet, the terminology used to describe scales differs among disciplines. In ecology and to some degree in physical geography, scale is often defined in terms of *grain* and *extent*, denoting the resolution of the measurements or observation in data and analysis, and the spatial or temporal magnitude over which observations are made (e.g. study area or duration of the study) (Sayre 2005; Hay 2005; Turner et al. 1989). Scale is also used to refer to measurement tools and instruments in experimental and quantitative research (Brunsdon 2018), while scale is understood and heavily debated as one dimension of complex socio-spatial relations in human geography and socio-spatial theory (Brenner 2001; Jessop et al. 2008; Marston 2000). Moreover, while the denominators 'small-scale' and 'large-scale', for example, are commonly used to refer to small or large phenomena with regard to scales of space, time, or quantity, cartographers and others concerned with mapping environmental change use the terms in the sense of map scales, i.e. small-scale refers to maps covering large areas (e.g. continents), while large-scale maps represent smaller areas (e.g. a city district) (Goodchild 2011). Such terminology differences give rise to confusion and risk hampering interdisciplinary collaboration in practice.

The scale challenge for interdisciplinary human–environment research

While it is beyond the scope of this introduction to present an in-depth review of the diverse scholarly debates on scale in different disciplines, we see at least three barriers for interdisciplinary human–environment research seeking to work across scales. First, many human–environment interactions are characterised by scale mismatches between the social and ecological processes embedded in them (Cumming et al. 2006). The organisation of human societies in communities, cities, or countries rarely matches the extent of the ecosystems or biophysical processes they act in. For interdisciplinary research, disciplinary conventions for focus of study, conceptual backgrounds, and data sources or availability, challenge common research designs (Dirnböck et al. 2013). Political scientists and economists interested in human–environment issues, for example, often study human decision-making and behavioural change at various levels of decision-making and may use surveys, official statistics, or census data related to administrative boundaries that predefine the scale of study (Moss and Newig 2010; Veldkamp et al. 2011). Ecologists and physical geographers interested in the patterns, processes, and spatial extent of ecological or landscape change, in turn, may for example rely on observational data from field surveys that determine the grain and extent of their studies to a watershed or biomes (Semper-Pascual et al. 2020), while remote sensing analyses may be framed by the availability of satellite images and their resolution (Moon et al. 2021). Combining the results from such diverse research approaches in cross-scale analysis is thus often challenging.

Second, the process of scaling results and knowledge differs between research domains. Scaling overall refers to the translation of information and knowledge from one scale to another, including upscaling and downscaling results or rescaling governance models (Hay 2005; Newig and Moss

2017). This is both an empirical and analytical challenge, since physical and ecological processes scale differently than social processes (Niewöhner et al. 2016). For example, the ecological properties of a tree, a coppice, and a forest diverge and scale in completely different ways than do the social properties of an individual, a family, and a society. Upscaling or downscaling data or results, moving from the specific to general understanding, establishing causal relations, or making identified solutions applicable at different scales thus require substantially different methodological and theoretical approaches depending on the object of the study.

Finally, at a more fundamental level, epistemological approaches to the concept of 'scale' differ among disciplines from realist to constructionist perspectives (Manson 2008; Marston 2000; Moore 2008; Zhang et al. 2014). Realist scale perspectives rely on the premise that scales and scale levels exist independently of the object or process being studied and of the observer (Sayre 2005). Human–environment interactions are viewed as scale dependent in the sense that certain phenomena and processes occur naturally at certain scales, such as habitats for different species. Analytically, the challenge is to identify the best apparent fit between the scale of analysis and the specific change or process of interest (Manson 2008). Realist accounts of scale are generally used in the natural sciences and are complemented by hierarchy theory that contributes with a distinction between absolute scales with independent levels that can be objectively measured, and relative scales with interdependent levels related to and defined by the object or process under study (Gibson et al. 2000; Manson 2008). In contrast, constructionist perspectives on scales are based not only on the proposition that knowledge about the world is socially constructed, but also that scales are actively created through the research and through political processes that over time manifest in material reality as well (Manson 2008; Marston 2000). Scale terminology and metaphors such as *local*, *regional*, *national,* and *global* are thus not neutral or objective, but embedded in discursive and political power relations. It is therefore crucial to examine how such metaphors are constructed for a particular analytical or political purpose, rather than understanding them as given a priori (Beck et al. 2017; Howitt 1993, 1998). Although constructionist notions of knowledge production in human–environment research acknowledge that a material reality exists, this reality can never be divorced from the concepts and categories used to describe it, including analytical scales (Jones 2002; Niewöhner et al. 2016). Human geographers, anthropologists, political ecologists, and political scientists, for example, have used constructionist perspectives on scale to show how particular scales can be politically and linguistically constructed and manipulated with material impacts in human–environment systems (Marston et al. 2005; Neumann 2009; Newig and Moss 2017; Swyngedouw 2004).

Bridging scales

The discussions about these fundamental epistemological differences around scales, and their manifestations in different terminology, scaling challenges and scale mismatches are not new (Ahlborg and Nightingale 2012; Reid 2006). Efforts to bridge both spatial scales and knowledge domains were already at the centre of the Millennium Ecosystem Assessment in the early 2000s (Hay 2005; Reid et al. 2006). Yet, they continue to challenge researchers seeking interdisciplinary collaboration on complex human–environment relations. Recently, debates in the context of the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem services (IPBES) related to Nature's Contribution to People are advancing the scale bridging efforts by presenting novel ways of weaving together generalised and context-specific perspectives at multiple scales (Díaz et al. 2015; Hill et al. 2021).

In this paper, we join these debates with the aim of examining the day-to-day problems and tensions, both theoretical and practical, that human–environment researchers face when dealing with cross-scale issues, as well as to scan solutions that enable spaces of collaboration for 'bridging scales'. Our aim is thus not to 'settle' any (inter)disciplinary discussions on the definition of scales and scaling—which is neither possible, nor necessarily desirable—but rather to use the notion of 'bridging scales' as a starting point for creating a better understanding of plural perspectives on scale in order to improve interdisciplinary collaboration in terms of theory, data, methods, and findings. A central argument is thus that we need to identify leverage points for change (Abson et al. 2017; Dorninger et al. 2020; Meadows 1999) in the current academic system to foster spaces for exchange and learning that enable a diverse scale understanding.

We take our cue for this collaborative research from the challenges we have encountered as a group of early-career researchers from diverse disciplinary backgrounds from human and physical geography, through hydrogeology, forestry and conservation science, and remote sensing, to environmental policy and institutional economics. Through our collaborative work at the Integrative Research Institute for Transformation of Human–Environment Research (IRI THESys) at the

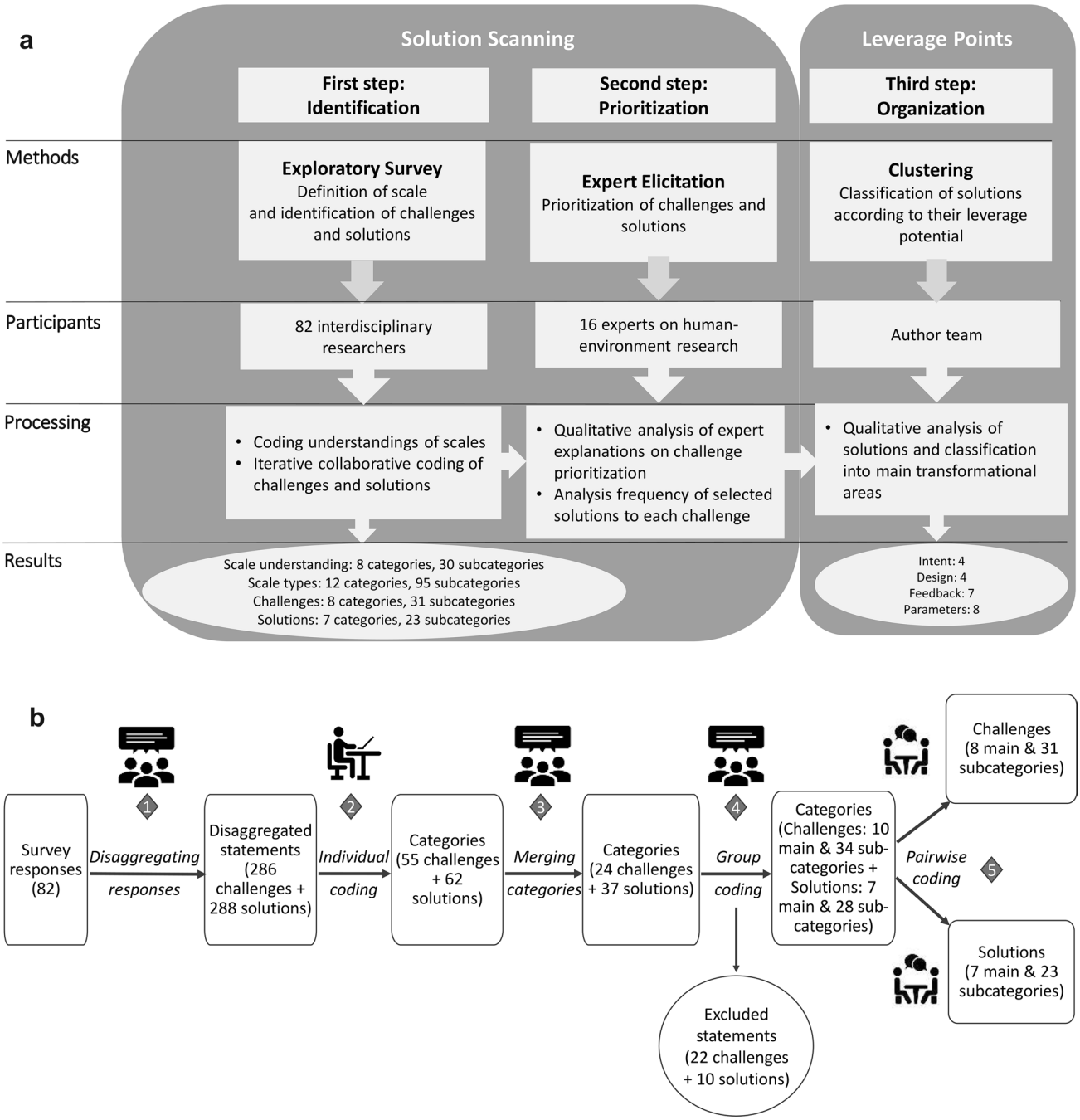


Fig. 1 Methodological flowchart of **a** our three-step approach in the identification, prioritisation, and organisation of challenges and solutions in bridging scales and **b** coding process for identifying challenges and solutions

Humboldt-Universität zu Berlin, we encountered several points of tension related to our different understandings of scale as a concept and a research frame. In this paper, we use these tensions and the perspectives presented above as a starting point to pursue three main objectives. First, we identify the main challenges for bridging scales among human–environment researchers; second, we identify a set of solutions for those challenges that can advance interdisciplinary discussions

and practical collaboration in human–environment research. Finally, we analyse the solutions according to their leverage potential for change across three systemic arenas in the academic system, namely individual researchers, research institutions and organisations, and the wider academic structures.

Methods

To address our objectives, we applied a three-step methodology (Fig. 1a). We used an extended version of the classical solution-scanning exercise to first identify the challenges experienced by human–environment researchers when bridging scales, and second to determine the most suitable solutions, before asking experts to prioritise these solutions. Solution scanning is a stepwise methodology used to identify a list of actions, interventions, or approaches that respond to a challenge, and that can be used to set research agendas, or identify potential policy interventions in decision-making processes (Dicks et al. 2017; Sutherland et al. 2014). Solution scanning proceeds by first defining an objective or a challenge. The objective can be deduced from knowledge gaps in the literature, or from societal needs and concerns (Pullin et al. 2013). Then a group of experts is asked to use their experiences to identify actions that can leverage change towards the stated goal. In the last step, the proposed solutions are listed and distributed to the experts to be assessed and prioritised according to given criteria (Hernández-Morcillo et al. 2018; Plieninger et al. 2018).

Following the solution-scanning exercise, we used the notion of leverage points to analyse the potential of the identified solutions to induce changes in the academic system that could facilitate bridging scales in interdisciplinary human–environment research. The leverage point notion is based on a system perspective, where interventions and solutions are considered based on their capacity to induce shallow or deep changes (Abson et al. 2017; Dorninger et al. 2020; Meadows 1999). In her seminal paper on leverage points, Meadows (1999) identified twelve types of system interventions that were later synthesised by Abson et al. (2017) into four types of system characteristics organised from the shallowest to the deepest: parameters, feedbacks, design, and intent. Parameters are modifiable, mechanistic characteristics or physical elements of a system such as incentives, standards, or factors typically targeted by decision-makers and individuals. Feedbacks are the interactions between elements within the system that drive internal dynamics or provide information regarding desired outcomes. Design characteristics relate to the social structures of information flows, rules, power, and self-organisation that manage parameters and feedback. Finally, intent characteristics relate to the norms, values, and goals embodied within the system of interest and the underpinning paradigms from which they arise (Abson et al. 2017).

First step: identification of challenges and solutions to bridging scales

Exploratory survey design

To gain a broad understanding of the challenges interdisciplinary human–environment researchers are facing in relation to scales and scaling, as well as to elicit as many ideas for solutions as possible, we conducted a survey among the participants of the KOSMOS Conference "Navigating the Sustainability Transformation in the 21st Century" organised by the Humboldt-Universität zu Berlin in August 2019.[1] The KOSMOS Conference was attended by 316 people, primarily researchers and students, as well as a few practitioners, from a broad range of fields to discuss today's great challenges for sustainability, and hence presented a good setting to carry out the survey.

The survey was designed in four parts: (1) understanding of the term 'scale' and relevant 'scales' in the respondents' research; (2) listing the three main challenges in relation to bridging scales; (3) identification of the three most effective solutions related to the named challenges; and (4) characterising respondents' profiles including education, current research topic, and biographical data.

A total of 82 people participated in the survey (25.9% of all participants) with an almost equal gender distribution (50% female, 48% male, and 2% not specified). The vast majority were academic professionals and students (90% of the respondents), and most of the respondents came from or had their primary employment in Germany (74%). The respondents' reported disciplines were mainly sustainability (27%), natural (23%), and social sciences (12%). A quarter of respondents declared that they work in interdisciplinary settings. When considering their current field of research,

[1] The conference marked the 250th birthday of Alexander von Humboldt and presented a wide range of research under seven headlines: "Publics and ethics of sustainability", "Democracy, governance, and societal conflicts in a globalized world", "Economies beyond unlimited growth", "Limited land—a local to global perspective", "Urban and rural: a necessary partnership", "Water and biosphere: preconditions of survival", and "Climate Change: biophysical impacts and societal responses".

many respondents with a background in the socio-economic, agriculture, and forestry sciences indicated that they had moved from a disciplinary background into more interdisciplinary work.

Coding understandings and types of scales used by the respondents

To analyse the survey responses regarding 'understanding of scales', we coded the full answers from the survey ($n = 82$) together as a team. In a first round, answers that were conceptually similar were grouped together under a conceptual category. Some answers included more than one component and were coded under more than one category, which resulted in a total of 137 entries. In a second round of coding, the categories with less than two entries were re-organised and merged into other categories. We then consolidated the categories in a consensual process (Fig. 1a, see also Table 1 in the Supplementary Material).

To analyse the 'types of scales used by the respondents', we counted the frequency of identical or similar answers and grouped these into categories. Also here, several answers were placed into more than one category resulting in a total of 321 entries. We then consolidated the categories (Fig. 1a, see also Table 2 in the Supplementary Material).

Coding of challenges and solutions

Before coding the challenges and solutions, we disaggregated survey responses containing multiple components into individual statements (Fig. 1b, step 1). This resulted in 286 individual challenges and 288 individual solutions. We then coded the challenges and solutions manually in several rounds of coding. In the first round, we individually categorised the statements and proposed overarching categories (step 2). Subsequently, we collaboratively merged similar categories identified by different coders agreeing on a common set of categories (step 3). In a second round of coding, we discussed the content of the emerging categories, reassigned and recoded some statements, and grouped thematically similar categories under the same overarching heading to consolidate challenges and solutions into main categories and subcategories (step 4). Two of the main solution categories contained statements that were aligned in content to the extent that subcategories were not necessary. At this stage, we also discarded several statements containing vague or unclear answers, such as incomplete sentences or one-word answers. Finally, in a third round of coding, we split into two groups to check the consistency of the statements coded in each category, and to agree on possible re-categorisations and new categories (step 5).

Second step: prioritisation of challenges and solutions

Expert identification

The second step of our study aimed at connecting and prioritising the key challenges with suitable solutions and involved an online expert elicitation process. We approached experts of different disciplinary backgrounds but working in the field of human–environment research and with expertise in questions of scale and scaling. We identified experts through (1) suggestions made by survey participants; (2) established scholars identified through the literature; and (3) the co-authors' scholarly network. In addition to these criteria, we considered geographical representation, gender balance, and a diversity of disciplinary backgrounds from across the social and natural sciences, as well as interdisciplinary fields such as sustainability science as key features for finding potential experts. Our final list included 59 scholars (39 male, and 20 female), who were approached via email.

Sixteen experts participated in the elicitation process (response rate of 27%). They were four women, eleven men, and one undisclosed, and the majority were from Europe with a few from South and North America, as well as Africa. The experts had a wide range of disciplinary backgrounds within the social and natural sciences, as well as some with interdisciplinary profiles. Several of the experts indicated that they had made a move from more disciplinary fields of research, e.g. mathematics, geography, and economics, during their PhD degree to more interdisciplinary fields of research, including environmental resource management, land system science, and sustainability science (see Table 3 in the Supplementary Material).

Questionnaire design

We used an online survey tool with a questionnaire divided into three sections for the expert elicitation process. First, we asked the experts to choose the three challenges deemed most pressing and to elaborate on the reasons for their choice. For the sake of clarity, we presented the experts with the main challenges categories ($n = 8$) instead of the subcategories ($n = 31$). Second, we asked the experts to choose up to three solutions for each of the challenges and to explain their selection. Here, we presented the experts with the full list of solution subcategories ($n = 23$) to provide a full range of options and allowed the experts to provide suggestions for implementing the solutions. We presented both challenges and solutions as full sentence statements and provided lists elaborating and explaining the content of each category.

Table 1 Survey results of answers to the question 'What are the relevant/important types of scale in your research?' Only main category and largest subcategories are shown here

Code	Main category	Largest sub-group (total entries)	Main category responses in % (total entries)
A	Spatial scales	Global (23)	28.7 (92)
K	Thematic scales	Geographical (6), economical (6)	12.1 (39)
B	Spatial–political scales	National/country (24)	9.3 (30)
D	Social scales	Human/people (8)	9.3 (30)
H	Political/administrative/institutional scales	Institutional (7), political (7)	8.7 (28)
C	Temporal scales	Temporal general (20)	8.4 (27)
E	Natural scales	Natural system (4), ecosystem (4)	7.2 (23)
F	Socio-natural phenomena	Climate change (6)	4.7 (15)
I	Interaction/movement/change	Multi-/cross scale (5)	4.4 (14)
L	Scale specific	Map scales (5)	3.4 (11)
J	Measurement scales	Likert (2)	1.6 (5)
G	Biophysical scales	Biophysical general (2)	1.9 (6)
M	Other	Specific theories (1)	0.3 (1)
	Total		100 (321)

Then, we asked which scales they primarily used in their work and finally we asked for profile information.

Coding process and analysis of expert answers

We analysed the experts' answers related to their definition of scales using the coding scheme developed based on the survey responses. While all the experts' answers fell within the identified main scale categories, they also brought attention to several new types of scales, which we coded into two new subcategories.

For analysing the challenges and solutions prioritised by the experts, we first ranked the challenges in terms of number of experts prioritising them and second grouped the selected solutions for each of the challenges. We qualitatively analysed and compared explanations for the choice of challenges and the elaborations related to solutions.

Third step: organising the solutions according to their leverage potential

To cluster the different solutions according to their potential for system-wide change and sustainability transformation, we analysed the prioritised solutions resulting from the expert elicitation using the notion of leverage point to sustainability transformation (Abson et al. 2017; Dorninger et al. 2020; Meadows 1999). For that purpose, we first defined our system of interest as the academic system concerned widely with human–environment interactions. This comprises the different disciplines, research organisations, researchers, communication structures, and funding schemes. Then, we divided the author team into two groups to discuss each solution and assign them into one of the four types of system characteristics: intent, design, feedbacks, and parameters. We then compared both groups' outcomes and reached a final classification by consensus. Within each type of system characteristics, we sorted the solutions according to their perceived relations to the previous and next type.

Results

Scale definitions

The survey respondents' understandings of scale showed the breadth of definitions attached to this concept in human–environment research and as represented by their diverse backgrounds. Several of the respondents noted how their disciplinary training influenced their understanding of scale, while others pointed out how the multiple definitions and uses of scales challenge interdisciplinary research at a fundamental level. One respondent pinpointed this diversity by stating that it is "hard to define the 'term', I guess it depends on one's area and how concrete you want to be. e.g., it can be about relatedness, e.g., of human scale and the universe, more philosophical. Or simply a level, a size of something as in maps" (Survey-ID66).

In the coded responses, the majority referred to specific spatial associations like "local" or "continental" ($n=42$) and descriptive terms like "level" and "range" ($n=31$), while fewer referred to how 'scale' can be defined by its characteristics depending on the context it is applied in (e.g. referring to size, range or scope) or the relations it is used to describe (e.g. between time and space or material-immaterial world) ($n=15$). In addition, a large number of the coded responses

linked scale to the research process as a particular perspective or tool of measurement ($n=22$), while others more closely related the term to the process of establishing units of analysis ($n=8$) and boundaries for the scope of research ($n=7$). Finally, a few responses emphasised how we need to engage with scale through more critical perspectives related to power, conflict, and diversity ($n=4$).

The diversity of responses related to the understanding of scale was mirrored in multiple types of scales used by survey respondents in their own research (Table 1). Spatial scales and levels, e.g. local or global, were by far the most widely used type of scales among our respondents, followed by spatial–political scales, political/administrative scales, and temporal scales. In addition, many respondents defined the type of scale they work on in thematic terms such as "human scale vs. the economy", "global scale of SDG implementation" or "scale of interlinks between consumers and producers" (referred to as "thematic scales" in Table 1).

The experts' use of scale was also very diverse, and largely mirrored that of the survey respondents. The majority of experts defined their work in relation to spatial scales such as local, regional, or global, and several worked on spatial political scales or political/administrative/institutional scales. Moreover, some of the experts indicated that their work mainly related to change and cross-scale interactions including upscaling, downscaling, and local–global interaction. In addition to the categories used by the survey respondents, two of the experts mentioned additional types of scales related to "data" and "social–ecological systems".

Challenges for bridging scales in human–environment research

Identification of challenges

We identified 31 specific challenges for bridging scales in human–environment research grouped into eight main categories (hereafter, 'main challenges'), of which *differences in research approaches*, the *process of scaling*, and *communication* had the highest frequency in the survey responses (Table 2). Less prevalent, although still noticeable, were challenges related to structural problems within the *academic system, differences in problem definition*, and problems related to the personalities and *profiles of the researchers*. Finally, some responses were concerned with issues related to fundamental *conflicting perspectives* among social and natural researchers, and transdisciplinary challenges seeking to bring knowledge *from research into action*.

Prioritisation of challenges

The eight main challenges were prioritised between nine and three times by the sixteen experts (Table 2). Also, among the experts, the most prominent challenge was *differences in research approaches* prioritised by nine of the experts. Here, the experts highlighted how research approaches in different fields often are designed to target different scales making collaboration challenging. Several experts also pointed out that different research approaches make it difficult to establish causality across scales, to balance the level of detail and depth of analysis, as well as generalising results through upscaling or downscaling.

The second most prominent challenge relates to structural challenges embedded in the *academic system*. The experts pointed to problems in the current funding structures noting for example that limitations on funding and time make researchers focus on a single case for the sake of feasibility. Moreover, it was emphasised that the challenges of bridging scales are closely related to and embedded in the barriers to pursue interdisciplinary research and interdisciplinary research careers in the education system, evaluation structures, and scientific journals.

On a shared third place, three of the challenges were prioritised by six experts. The first was fundamental differences in *problem definition*, i.e. in the way human–environment interactions are understood, conceptualised, and approached in different fields. Here, it was noted that the inherent complexity of human–environment systems such as scale mismatches between social and ecological processes is a fundamental challenge, complicating the establishment of appropriate system boundaries and units of analysis both in spatial and temporal terms. The other challenge was *conflicting perspectives* among social and natural scientists. One expert elaborated stating that "conflicts start with the different meanings, definitions, and delineation of 'space' in cultural and physical geography and end in a growing lack of understanding between the social and natural sciences" (Expert-ID11). The challenge is then to negotiate different understandings and find ways of compromising and balancing disciplinary strengths and interdisciplinary collaboration. Lastly, six experts pointed to transdisciplinary challenges related to bringing knowledge *from research to action*. This was particularly related to scaling up actionable knowledge and bridging knowledge on problems and solutions between actors working at different levels and scales. One of the experts, for example, argued that the problem "goes beyond accessibility of specialised knowledge: it deals with the question of how to generate common understandings among different levels of action" (Expert-ID19). These fundamental transdisciplinary issues are related to the inclusion of different perspectives in problem definition, research agendas, and research finance.

The final three challenges were *process of scaling*, *communication*, and *the researcher's profile* prioritised by five, four, and three experts, respectively. One of the issues highlighted concerning the *process of scaling* was the clash

Table 2 The main categories and subcategories of challenges for bridging scales in human–environment research identified through the survey ($N = 264$), and the frequencies of coded responses

Label	Categories	Number of experts	Frequencies of survey responses (%)
Different research approaches	Differences in research approaches create challenges	9	19.7
	Data collection, data sharing, data integration		7.2
	Difficulty to integrate different methods across disciplines		3.8
	Lack of effective methods and tools for "bridging scales"		3.0
	Establishing and tracing causal links between and across scales		2.3
	Lack of analytical frameworks to deal with scale complexities		1.9
	Over-attention to a small number of research areas (geographic, thematic)		1.5
Academic system	Structural challenges embedded in the academic system	7	11.4
	Lack of interdisciplinarity in the academic system		3.0
	Structural barriers in the institutional setup of academia		2.7
	Time or financial resource constraints limit cross-scale research		2.3
	Conflict between the ideals of science and the realities of scientific practice and performance		1.9
	Lack of interdisciplinary education and incentive structures for the interdisciplinary careers		1.5
Problem definition	Empirical understanding of human–environment interactions (problem definition)	6	10.6
	Identifying and understanding specific human–environment interactions and the relevant scales to study them		4.9
	Complexity of human–environment interactions		3.4
	How do we define the boundaries of the systems/phenomena studied? (Unit of analysis)		1.1
	The emergence of different phenomena at different scales of human–environment systems		1.1
Conflicting perspectives	Conflicting perspectives in the natural and social sciences	6	7.6
	Conflicting values and visions on priorities for human–environment research		3.0
	Different understandings of scales in the natural and social sciences		3.0
	Scepticism on the relevance of and possibility for "bridging scales"		1.5
From research to action	Transdisciplinary challenges related to bringing knowledge from research to action	6	5.7
	Including and engaging non-academic partners in the research process		3.8
	Scaling solutions to make actionable knowledge accessible at different scales		1.9
Process of scaling	The process of scaling as a problem in interdisciplinary research	5	18.9
	Integrating and addressing different scales		8.0
	Difficulties related to upscaling data and results		4.5
	Lack of common theory of scale		3.4
	Difficulties related to downscaling data and results		3.0
Communication	Communication challenges within and beyond the research process	4	17.0
	Difference in understanding creates internal communication problems among researchers		5.7
	Establishing common vocabulary and terminology		4.5
	Organising and communicating between different science–policy–practice actors across scales		3.8
	Difficulties related to the translation of terms between languages		3.0
Researcher's profile	The researcher's profile creates challenges for bridging scales	3	9.1
	Unwillingness to consider different perspectives on scales		4.9
	Different perspectives and priorities among researchers		2.3
	Limited perspectives due to different socio-cultural backgrounds		1.9

The challenges are ordered according to the experts' prioritisation of challenges (see full explanation of the categories in Table 4 in the Supplementary Material)

Table 3 The main solution categories and subcategories identified through the survey ($N=277$), and the frequencies of coded responses (%) for bridging scales in human–environment research (see full explanation of the categories in Table 5 in the Supplementary Material)

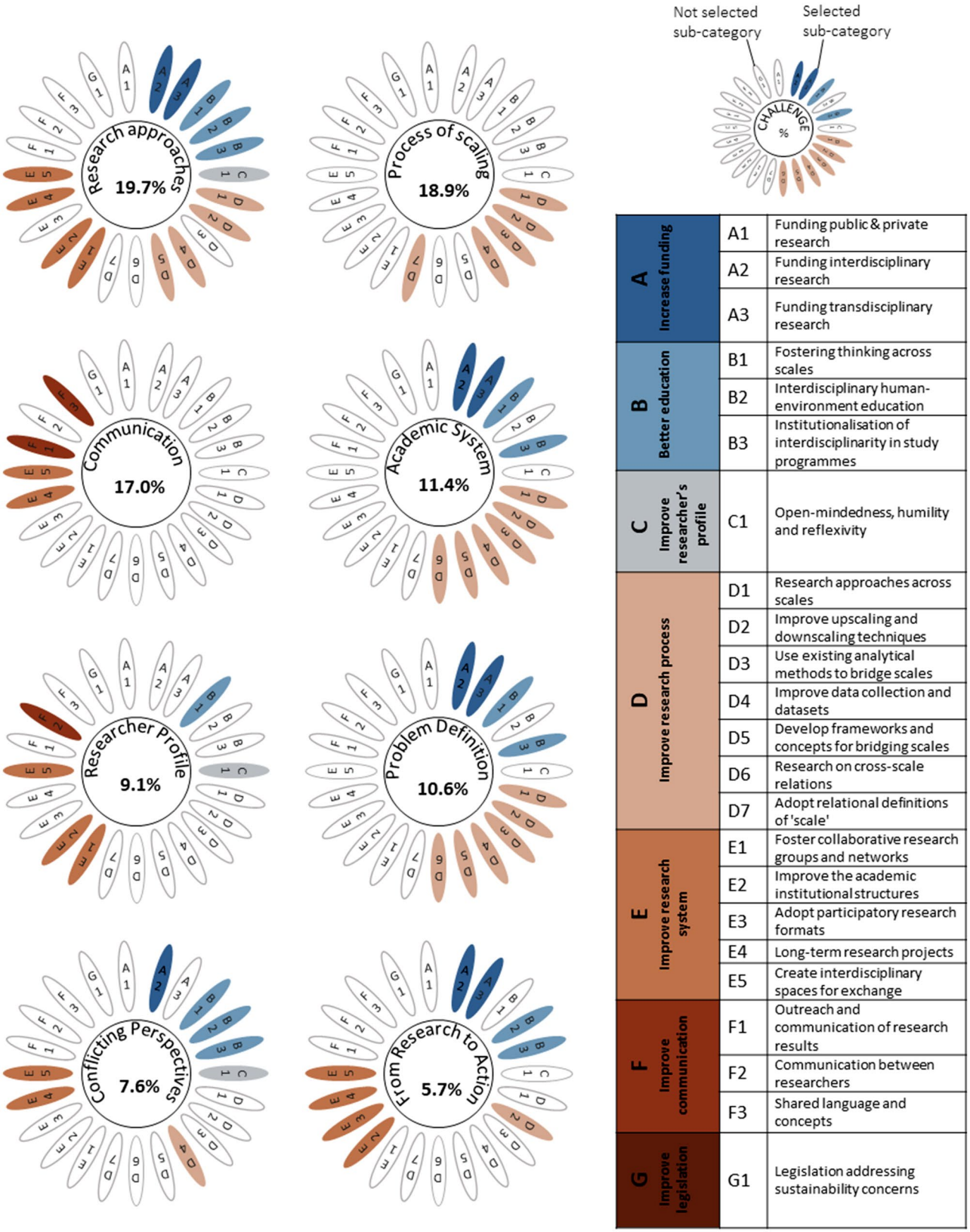
Label	Category	Frequency (%)
A. Funding	Better research funding	5.4
A1	Increase research funding in public and private research	1.8
A2	Increase funding for inter- and multi-disciplinary human–environment research	2.5
A3	Increase funding for transdisciplinary research	1.1
B. Education	Better education	7.6
B1	Education and training that foster thinking across scales	2.2
B2	Promote interdisciplinary human–environment education that provides perspectives from more than one discipline	2.9
B3	Institutionalisation of interdisciplinarity in study programmes	2.5
C. Researcher's profile	Improving the researcher's profile through open-mindedness, humility and reflexivity	12.3
D. Research process	Improving the research process	36.1
D1	Develop better research approaches to consider both processes and impacts across scales	11.6
D2	Improve techniques for upscaling and downscaling data, methods and results	5.8
D3	Use existing analytical methods to bridge gaps of understanding between scales	7.9
D4	Improve data collection and datasets, as well as linking data from social and natural research	4.0
D5	Develop better analytical frameworks and concepts for bridging scales in human–environment research	1.8
D6	Ensure a research focus on issues on different scales, as well as on 'scale' as an object of study in itself	2.9
D7	Adopt a relational definition of 'scale'	2.2
E. Research system	Changes to the research system and environment	23.1
E1	Foster more collaborative research groups and networks at individual, working group and institutional levels	7.9
E2	Improve the institutional structures of the academic research environment	5.1
E3	Adopt more participatory research formats and improve public participation in research	3.6
E4	Foster long-term research projects	2.2
E5	Create interdisciplinary spaces for academic exchange	4.3
F. Communication	Improving communication within and beyond research	13.4
F1	Improve outreach in relation to communication of research results and implications	6.1
F2	Improve communication between researchers from different scientific cultures when working in joint projects	1.4
F3	Commitment to discussion of shared language, definitions and concepts among collaborating researchers	5.8
G. Legislation	Improve legislation addressing sustainability concerns at multiple societal levels	2.2

between the 'high-level' abstract theories of scale and systemic understandings of complexity on the one hand, and the localised and small-scale empirical examinations of specific phenomena on the other. Concerning *communication* challenges, the main issues emphasised by the experts concerned creating common understandings of scale terminology and concepts, especially arising when needing to work across epistemological boundaries in social–ecological research. Furthermore, it was pointed out that cross-scale research in international contexts requires collaboration among scientists of different cultural and linguistic backgrounds, who predominantly need to collaborate in English. Finally, among the three experts that selected the *researcher's profile* as a challenge for bridging scales, it was stated that our disciplinary backgrounds often socialise us to particular scales of analysis. Furthermore, there is still a need for cultivating open-mindedness to different research approaches in and among different scientific communities. As one of the experts highlighted, researchers' different socio-cultural backgrounds can create different perspectives that are hard to overcome.

Solutions to bridging scales in human–environment research

Identification of solutions

From the survey, we identified 23 solutions under seven main categories (Table 3). By far, the survey respondents most frequently referred to solutions related to improving the *research process* with more than 100 individually coded suggestions. In addition, responses focused



A Increase funding	A1	Funding public & private research
	A2	Funding interdisciplinary research
	A3	Funding transdisciplinary research
B Better education	B1	Fostering thinking across scales
	B2	Interdisciplinary human-environment education
	B3	Institutionalisation of interdisciplinarity in study programmes
C Improve researcher's profile	C1	Open-mindedness, humility and reflexivity
D Improve research process	D1	Research approaches across scales
	D2	Improve upscaling and downscaling techniques
	D3	Use existing analytical methods to bridge scales
	D4	Improve data collection and datasets
	D5	Develop frameworks and concepts for bridging scales
	D6	Research on cross-scale relations
	D7	Adopt relational definitions of 'scale'
E Improve research system	E1	Foster collaborative research groups and networks
	E2	Improve the academic institutional structures
	E3	Adopt participatory research formats
	E4	Long-term research projects
	E5	Create interdisciplinary spaces for exchange
F Improve communication	F1	Outreach and communication of research results
	F2	Communication between researchers
	F3	Shared language and concepts
G Improve legislation	G1	Legislation addressing sustainability concerns

Fig. 2 Experts' prioritisation of solutions for each of the main challenges. The circles in the centre illustrate the challenge and the frequency of survey respondents, and the coloured leaves indicate the experts' choice of solutions for each challenge. The labels in the legend mirror the solution categories in Table 3, but have been shortened for readability

on solutions related to improving the *research system* through e.g. fostering better environments for collaborative research groups and networks, and developing long-term research projects that can enable the interdisciplinary exchange. In addition, suggestions for working towards better *communication* within and beyond academia featured frequently among the responses, as did solutions related to improving the *researchers' profile* towards more open-mindedness, humility, and reflexivity among researchers working on interdisciplinary topics. The remaining solutions were grouped around topics such as improving interdisciplinary *education* and training that foster thinking across scales and increasing *funding* for inter- and transdisciplinary research.

Linking challenges with solutions and prioritisation of solutions

The results of the expert elicitation showed that the experts prioritised a multiplicity of solutions for the challenges related to differences in *research approaches*, *conflicting perspectives*, and *from research to action*, as well as to the *researchers' profiles* (Fig. 2). For other challenges, i.e. the *process of scaling* and *communication challenges*, the prioritised solutions were focused on a few targeted areas.

Looking across the prioritised solutions, suggestions for improving education that fosters thinking across scales (B1) and providing students with interdisciplinary competences (B2) feature prominently for several of the challenges, mainly for tackling *conflicting perspectives* and differences in *research approaches* related to scales. One expert emphasised that "training and education should prepare future researchers to arrive from a defined problem [to] a scale-crossing understanding" and continued by noting that "to be able to integrate data from various perspectives, requires a profound knowledge about scale issues, awareness raising of the scale issues and careful consideration in the design of the research process" (Expert-ID9). For five of the challenges, the experts highlighted the need for institutionalisation of interdisciplinary study programmes that consider diverse scale perspectives (B3). In contrast, one expert noted that while researchers trained interdisciplinarily are great at collaborating across knowledge domains, they often lack the in-depth theoretical and methodological knowledge that is associated with disciplinary training. To abate this, the expert proposed a stronger focus on fostering enlightened interdisciplinary collaborations among disciplinary scholars, and to foster long-term research projects that would allow this.

Another set of crosscutting solutions prioritised by the experts is improvements to the *research system* and environment (E). These solutions feature prominently in relation to the challenges concerning differences in research approaches, problems with the researchers' profiles, and transdisciplinary efforts in bringing research to action. The experts particularly pointed to the need for fostering more collaborative research groups and networks, and collaborative teams to enable data integration (Expert-ID25). Several experts also noted the need for creating more interdisciplinary spaces for academic exchange that for example can "enhance discussions and understanding of different languages" (Expert-ID13) and to use digital environments to build interdisciplinary collaborations in the absence of institutional structures.

The experts also focused on the need for improving the *research process* (D) as the solution to several scale challenges, with the main suggestions centering on the need for developing better cross-scale analytical frameworks, and methodological innovation related to upscaling and downscaling techniques. This included building better datasets, as well as linking existing datasets from the social and natural sciences since "most repositories are not interdisciplinary" (Expert-ID13). These efforts would require researchers to "set aside time and resources within a project to develop such a framework before starting the empirical data collection" (Expert-ID9). One expert also pointed to the need for adopting a relational understanding of scales to recognise "scale as an important part of research contexts that needs to be described" (Expert-ID22).

In relation to the challenges of communication and the researchers' profiles, the experts not surprisingly pointed to improvements through commitments of time and resources to discuss shared language, definitions, and concepts among collaborating researchers. Good communication skills were also emphasised by the experts highlighting the need for more open-mindedness, humility, and reflexivity among researchers regarding their own positions (C). This would allow researchers to adopt more inclusive practices and appreciate diverse research approaches, which will benefit not only the individual researcher's understanding but also the larger projects and programmes they are involved in. One expert summed up this position: "Hubris goes hand in hand with disciplinary divisions. A true researcher of wicked problems must recognise that she/he has only part of the solutions; and that her/his understanding of the problem is only partial" (Expert-ID19).

Finally, most of the proposed solutions tie into calls for more and better research funding of inter- and transdisciplinary research projects. Increasing funding was prioritised in relation to the challenges of structural problems in the academic system, problem definition and transdisciplinary projects. This was emphasised by one expert noting the need for more programmes "that contain multiple spatial and temporal scales within one common framework/research endeavour [this] takes time and money because they need to be large and long-lasting" (Expert-ID20), while another

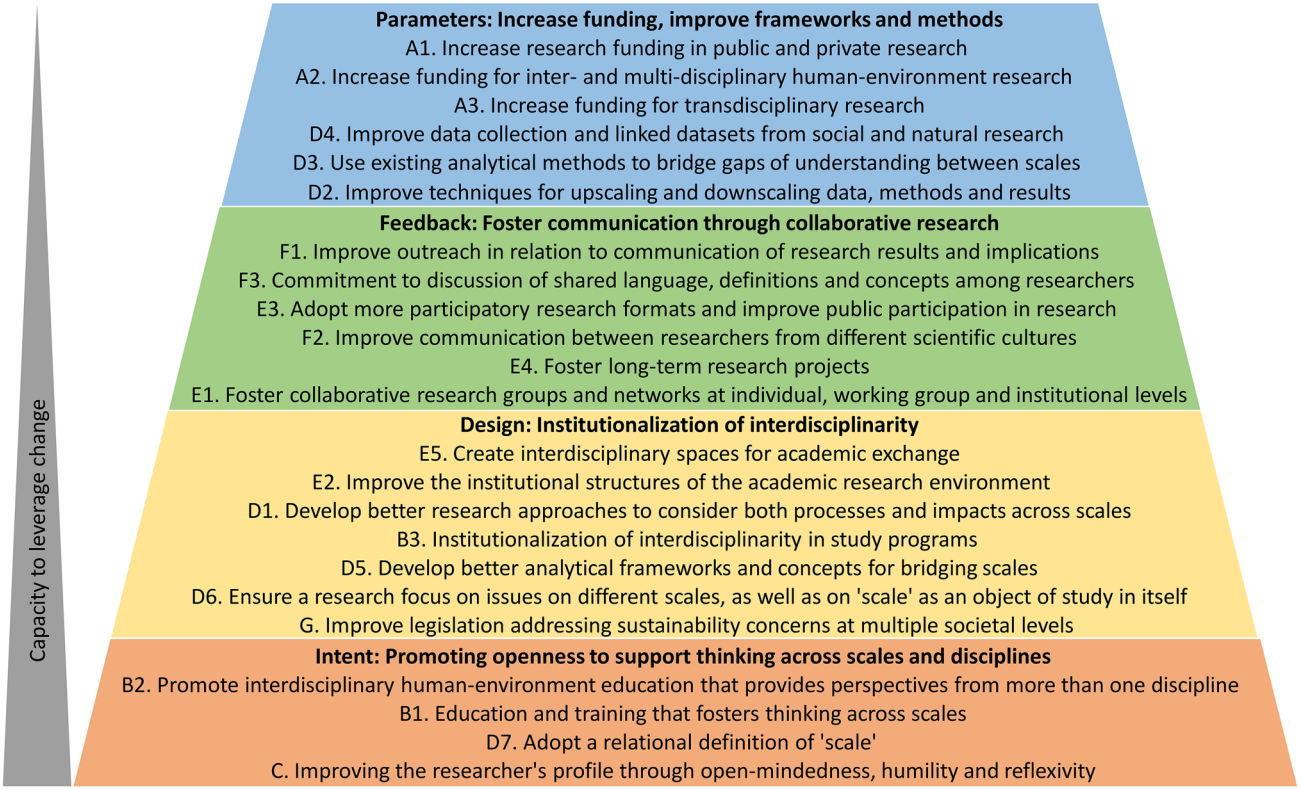


Fig. 3 System characteristics with the strategic solutions according to their potential to bridge scales in human–environment research. The figure is modelled on the leverage points framework presented by Meadows (1999) and adapted in Abson et al. (2017, Box 2)

added that more funding per se is not necessarily the solution but more targeted funding would be required to address the challenges of bridging scales.

Leveraging change for bridging scales in human–environment research

Our analysis shows that the identified solutions are crosscutting in terms of the challenges they address. Moreover, using the leverage point framework to analyse how the different solutions can be organised according to their potential to leverage change in the academic system (Abson et al. 2017; Dorninger et al. 2020; Meadows 1999), we argue that they need to be addressed across all four types of system characteristics from the deeper level of system intent and design to the shallower levels of feedbacks and system parameters (Fig. 3).

At the deepest and most fundamental step, the solutions in the intent category correspond to changes required for affecting researchers' openness and capacity to think across scales and disciplines. Actions to enhance researchers' capability for self-reflection, humility and open-mindedness are at the basis. Through education and training programmes as well as adopting a relational definition of scale, a deep mindset change can support the conditions needed to implement the rest of the strategic solutions. Once there is an openness and understanding of the importance of bridging scales, steps towards improving the design of the academic system to institutionalise cross-scalar and interdisciplinary human–environment research can be taken. Setting principles for addressing multiple societal levels, clarifying the research focus, and developing analytical frameworks are key steps toward the institutionalisation of interdisciplinary study programmes and research approaches that consider processes and impact across scales. Then, institutional structures that facilitate spaces for academic exchange can be created.

In a next step, solutions aiming at fostering communication can be implemented through the promotion of collaborative research networks and enabling long-term collaborations. These types of internal feedbacks in the academic system would ensure actions to improve communication among researchers from different disciplines using participatory formats. In addition, they could facilitate researchers' commitment to share their concepts and definitions of scale that is necessary to improve the

outreach and impacts of scientific results. Finally, more mechanistic solutions supporting the implementation of suitable analytical methods and techniques to bridge gaps or improve upscaling and downscaling data can be applied side by side with actions to increase the funding for inter- and transdisciplinary research.

Discussion

Bridging scales in human–environment research continues to challenge interdisciplinary researchers on both theoretical and practical levels. The challenges highlighted by our participants mirror the long-standing discussion around scales in the literature (Dirnböck et al. 2013; Pulver et al. 2018), including epistemological differences (Marston et al. 2005; Sayre 2005; Zhang et al. 2014), differences in terminology (Gibson et al. 2000), scale mismatches (Cumming et al. 2006), and scaling challenges (Newig and Moss 2017; Niewöhner et al. 2016; Reid et al. 2006). At the same time, the results show that these challenges are highly interconnected and that addressing them requires solutions across a wide range of interventions, from the specific to the systemic, and capacities, from the individual to the collective. Thus, bridging scales both entails an acknowledgement and better understanding of diverse scale perspectives, and the development of better methods, frameworks, and datasets that enable cross-scale analysis, as well as collective work to enable spaces that foster scale bridging at multiple levels within the academic system. As such, most of the identified solutions call for structural changes to enable shared agency from individuals and organisations, as well as contextual realisation to foster inter- and transdisciplinary education and research (Caniglia et al. 2021).

The three strategic arenas of agency to bridge scales

Based on the leverage potential of the identified solutions, we see three strategic arenas for intervention within the academic system, where change is required concerning bridging scales: (a) the individual researcher, (b) the communities, institutions, and organisations researchers collaborate and work in, and (c) the wider systemic structures of academia, including the funding bodies and framing conditions. These strategic arenas for intervention are embedded within and made up of each other. At the deepest and most foundational level, an individual commitment to openness and reflexivity, as well as to a practice of care (Care et al. 2021; Sellberg et al. 2021; Soininen et al. 2022) is required to successfully implement the solutions across systemic arenas. Yet, for enabling spaces for bridging scales both deep and shallow leverage points need to be engaged in each systemic arena of change.

In the following, we discuss how the solutions to bridge scales can be related to each of the three agency arenas, as well as the pathways to implement them. We provide examples from the literature to showcase how these solutions have been and can be operationalised and implemented in interdisciplinary human–environment research.

The self-reflexive and humble individual researcher

Individual researchers are at the core of the necessary changes required for advancing interdisciplinary research on and across scales. As individual researchers, we need to actively take responsibility for our own academic development in self-regulating learning settings (Ayish and Deveci 2019) by proactively seeking training and education to gain the necessary skills to bridge scales. This entails a commitment to self-motivated learning (Boekaerts 1988, 2011) and open-mindedness about the diversity of scale concepts (Ciesielski et al. 2017). Moreover, we need a commitment to reflexivity and humbleness on the limitations of our own disciplinary backgrounds, while applying sound research approaches, theoretical frameworks, and methods (Haider et al. 2018). At the same time, we need to ensure a research focus on cross-scale interactions and work collaboratively to develop better analytical frameworks and approaches that consider both processes and impacts at different scales (Cash et al. 2006; Folke et al. 2007). Here, open communication and a commitment to discussions of shared or diverging language and terminology holds a key role as a feedback mechanism that supports such collaborative work (Wada et al. 2020). Open communication, transparent data collection, and reporting of data are also essential for addressing the challenges of bridging scales by combining and improving datasets, and existing analytical methods for upscaling and downscaling results and methodologies (Bierkens et al. 2000). Finally, we should be aware of our position within the academic system (Hernaus and Černe 2021), and work to positively influence our institutions and organisations, as well as pushing for an agenda to change the structural conditions of the academic system as elaborated on below (Care et al. 2021).

Innovative scientific institutions and organisations

The second systemic change arena, where crosscutting solutions for bridging scales need to be implemented, is within scientific institutions and organisations. For the deeper leverage points, scientific institutions and organisations need to commit to interdisciplinary education and training programmes at all academic educational levels (Annan-Diab and Molinari 2017; Boone et al. 2020). Such efforts have

sprouted over the past decades, where both traditional universities and newer interdisciplinary research institutes have started recognising the need for interdisciplinary graduate and post-graduate education that teaches students to think about contemporary human–environment relations from multiple perspectives and across multiple scales.[2] In this way, scientific institutions and organisations are crucial for fostering open-minded and reflexive mindsets required for interdisciplinary human–environment researchers.

Another set of solutions relates to the design of the interdisciplinary research process and practice. Here, scientific institutions and organisations, as the providers of the necessary infrastructure for researchers to unfold cross-scale research, need to pay more attention to creating interdisciplinary spaces for exchange such as the Warwick Interdisciplinary Research Leadership Programme. This could also be in the form of resources for setting up collaborative research groups or working towards lowering barriers of collaboration between departments and researchers within institutions.

A key parameter and shallower leverage point to enable bridging scales in academic institutions and organisations is to progressively change incentive structures for high-pace, quick-fix research, and instead promote long-term research projects that engage in building trustful relations among multiple stakeholders and facilitate systemic changes (Mountz et al. 2015; Paasche and Österblom 2019). Leaders of scientific institutions and organisations with agency to shape funding bodies and set the legal frameworks in academic structures should use that power to collectively aim at long-term and collaborative research that is necessary to bridge scales (Care et al. 2021; Gordon et al. 2019).

Enabling structures in the academic system

Addressing the need for fostering long-term research projects that enable cross-scale inter- and transdisciplinary research points to the need for change at a more structural level. Funding agencies and academic policy-makers have the agency to address leverage points related to both funding structures, incentive structures and evaluation criteria. One example identified by our experts is the need for more funding for methodological proposals that seek to improve existing scaling techniques and link existing datasets. Lowering barriers for sharing data within and between research organisations also presents a 'low-hanging fruit' that could foster better research across scales through using and combining existing datasets. Good first steps in this direction include collaborations within and between universities with emphasis on open access datasets, data management and stewardship adhering to the FAIR principles (Wilkinson et al. 2016), information and communication technology infrastructure, and the growth of eResearch capabilities, involving the collaboration of multi-disciplinary teams of researchers, with data scientists and computer scientists, data stewards, and digital librarians (Anandarajan and Anandarajan 2010; Steel et al. 2019; Ware and Mabe 2015). These developments to the research landscape are enabling more flexible structures for sharing and exchanging data and results.

At a more fundamental level, funding agencies, academic review boards, and promotion committees should work toward revising criteria for the evaluation and selection of research projects and researchers. Currently, emerging debates across academia demonstrate the increased attention to how the dominating 'publish-or-perish' mentality inhibits cross-scale, long-term, interdisciplinary, and experimental engagement (Davies et al. 2021).

Within the current academic landscape, however, there are some encouraging movements toward creating spaces for a flourishing practice of long-term inter- and transdisciplinary research that bridges scales (Bennett et al. 2016; Geels 2002). Examples of such developments are the Programme of Ecosystem Change and Society community, and the different platforms and umbrella organisations at the research–policy–practice interface (e.g. IPCC, IPBES, and Future Earth) that work to form new coalitions and alliances for long-term and cross-scale interdisciplinary research (Sellberg et al. 2021). In addition, more and more cross-institutional networks for interdisciplinary collaboration are emerging. The Postdoc Academy for Transformational Leadership initiated by the Robert Bosch Stiftung[3] and hosted by four sustainability research institutes in Europe provides one example of a funding body promoting innovative space for education and exchange beyond the formally required education stages.

While simply increasing funding for long-term research and interdisciplinary education and exchange alone will not ensure a deep-seeded change in perspectives and competences to bridge scales, such initiatives exemplify the type of system parameters that should be addressed to take a first step towards enabling deeper leverage points and solutions.

Methodological reflection and limitations

The insights presented here were created by a team of researchers with different scholarly, as well as interdisciplinary training and thus a high awareness of challenges inherent to interdisciplinary research, particularly in the domain

[2] In northern Europe, for example: MSc in Climate Change at the University of Copenhagen; IRI THESys Graduate Programme and the MSc in Integrated Management of Natural Resources at Humboldt-Universität zu Berlin; and MSc in Environmental Studies and Sustainability Sciences at Lund University.

[3] See: https://www.bosch-stiftung.de/en/project/postdoc-academy-transformational-leadership/details.

of human–environment systems. Nevertheless, designing, conducting, and writing this work in an interdisciplinary team embodied—in several regards—the challenges we identified through the study. This became especially clear in the collective coding process of the challenges and solutions into categorisations, where we encountered diverging interpretations of the statements by survey respondents. We frequently created sub-groups in varying constellations to reflect on multiple sets of results, which we compared and discussed to create robust and consistent coding schemes. Open-mindedness and jargon-free communication successfully aided in overcoming some of the challenges related to language and definitions, as did consistent protocolling and attention to good organisation and moderation of joint discussion.

We attempted by all means to avoid biases in the respondents' gender, disciplinary background, or origin. Yet, the survey participants and experts consulted in this work stem from or conduct research in 20 countries across the globe. Nevertheless, our analyses of the participant demographics revealed a strong bias towards central European countries, most notably among the survey respondents (which dominantly work in Germany). As such, this study yields a highly international representation of the research community but may not cover all issues inherent to non-European academic systems with the same depth. We thus strongly encourage further research assessing differences between academic systems across all continents, and the determinants thereof.

Conclusion

Cross-scale interactions, scale mismatches, and diverging understandings and definitions of scale continue to challenge interdisciplinary human–environment researchers in their daily work. The main aim of this study was to concretise those challenges and to scan the most suitable solutions for advancing knowledge and research practice on scales in human–environment research. The objective was thus not to "solve" the problem of scale and scaling, nor to reach a consensus on definitions. Rather, our aim was to illustrate the diversity of understandings and methods of scaling that underpins and is needed for interdisciplinary human–environment research, as well as reflect on the conditions that would enable deeper understandings and practices of scaling at different levels from individual researchers to academic structures.

The main challenges ranged from issues related to differences in research approaches targeting different scales and conflicting perspectives on problem definition, over lack of structural interdisciplinarity and constraints on resources for long-term research collaboration, to issues with communication. The identified solutions pointed to the potential of improving the research process through open communication, data sharing, or new techniques for upscaling or downscaling results. Discussing the implementation of solutions in relation to their leverage potential, we argue that bridging scales in human–environment research requires work at three strategic arenas of agency in the academic system including individual researchers, research institutions and organisations, and in the wider structures of academia. At the individual level, bridging scales requires humbleness and open dialogue between researchers from different disciplines on scale concepts and scaling methods, as well as improved collaboration for operationalising them. In parallel, research institutions and organisations should develop their capacity to enable and nurture interdisciplinary spaces to flourish, while individual researchers and institutions alike should push for a development of the wider academic system that enhances the valuation and support of interdisciplinary and cross-scale initiatives.

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References

Abson DJ, Fischer J, Leventon J, Newig J, Schomerus T, Vilsmaier U, von Wehrden H, Abernethy P, Ives CD, Jager NW, Lang DJ (2017) Leverage points for sustainability transformation. Ambio 46(1):30–39. https://doi.org/10.1007/s13280-016-0800-y

Ahlborg H, Nightingale AJ (2012) Mismatch between scales of knowledge in nepalese forestry: epistemology, power, and policy implications. Ecol Soc 17(4). https://doi.org/10.5751/ES-05171-170416. Article 16

Anandarajan M, Anandarajan A (eds) (2010) E-research collaboration: theory, techniques and challenges. Springer Science & Business Media, Berlin. https://doi.org/10.1007/978-3-642-12257-6

Annan-Diab F, Molinari C (2017) Interdisciplinarity: practical approach to advancing education for sustainability and for the Sustainable Development Goals. Int J Manag Educ 15(2, Part B):73–83. https://doi.org/10.1016/j.ijme.2017.03.006

Ayish N, Deveci T (2019) Student perceptions of responsibility for their own learning and for supporting peers' learning in a project-based learning environment. Int J Teach Learn High Educ 31(2):224–237. https://files.eric.ed.gov/fulltext/EJ1224347.pdf

Barry A, Born G (2013) Interdisciplinarity: reconfigurations of the social and natural sciences. Routledge, London

Beck S, Esguerra A, Goerg C (2017) The co-production of scale and power: the case of the millennium ecosystem assessment and the intergovernmental platform on biodiversity and ecosystem services. J Environ Plan Policy Manag 19(5):534–549. https://doi.org/10.1080/1523908X.2014.984668

Bennett EM, Solan M, Biggs R, McPhearson T, Norström AV, Olsson P, Pereira L, Peterson GD, Raudsepp-Hearne C, Biermann F (2016) Bright spots: seeds of a good Anthropocene. Front Ecol Environ 14(8):441–448. https://doi.org/10.1002/fee.1309

Bierkens M, Finke P, De Willigen P (2000) Upscaling and downscaling methods for environmental research. Kluwer Academic, Dordrecht

Boekaerts M (1988) Motivated learning: bias in appraisals. Int J Educ Res 12(3):267–280. https://doi.org/10.1016/0883-0355(88)90005-5

Boekaerts M (2011) Emotions, emotion regulation, and self-regulation of learning: center for the study of learning and instruction, Leiden University, The Netherlands, and KU Leuven. In: Schunk DH, Zimmerman B (eds) Handbook of self-regulation of learning and performance. Routledge, London, pp 422–439

Boone CG, Pickett STA, Bammer G, Bawa K, Dunne JA, Gordon IJ, Hart D, Hellmann J, Miller A, New M, Ometto JP, Taylor K, Wendorf G, Agrawal A, Bertsch P, Campbell C, Dodd P, Janetos A, Mallee H (2020) Preparing interdisciplinary leadership for a sustainable future. Sustain Sci 15(6):1723–1733. https://doi.org/10.1007/s11625-020-00823-9

Brenner N (2001) The limits to scale? Methodological reflections on scalar structuration. Prog Hum Geogr 25(4):591–614. https://doi.org/10.1191/030913201682688959

Brunsdon C (2018) Quantitative methods III: scales of measurement in quantitative human geography. Prog Hum Geogr 42(4):610–621. https://doi.org/10.1177/0309132517717008

Cairns R, Hielscher S, Light A (2020) Collaboration, creativity, conflict and chaos: doing interdisciplinary sustainability research. Sustain Sci 15(6):1711–1721. https://doi.org/10.1007/s11625-020-00784-z

Caniglia G, Luederitz C, von Wirth T, Fazey I, Martín-López B, Hondrila K, König A, von Wehrden H, Schäpke NA, Laubichler MD, Lang DJ (2021) A pluralistic and integrated approach to action-oriented knowledge for sustainability. Nat Sustain 4(2):93–100. https://doi.org/10.1038/s41893-020-00616-z

Care O, Bernstein MJ, Chapman M, Diaz Reviriego I, Dressler G, Felipe-Lucia MR, Friis C, Graham S, Hänke H, Haider LJ, Hernández-Morcillo M, Hoffmann H, Kernecker M, Nicol P, Piñeiro C, Pitt H, Schill C, Seufert V, Shu K, Valencia V, Zaehringer JG (2021) Creating leadership collectives for sustainability transformations. Sustain Sci. https://doi.org/10.1007/s11625-021-00909-y

Cash DW, Adger WN, Berkes F, Garden P, Lebel L, Olsson P, Pritchard L, Young O (2006) Scale and cross-scale dynamics: governance and information in a multilevel world. Ecol Soc 11(2):8. https://www.ecologyandsociety.org/vol11/iss2/art8/

Choi S, Richards K (2017) Understanding interdisciplinarity. In: Choi S, Richards K (eds) Interdisciplinary discourse: communicating across disciplines. Palgrave Macmillan, London, pp 39–69. https://doi.org/10.1057/978-1-137-47040-9_3

Ciesielski TH, Aldrich MC, Marsit CJ, Hiatt RA, Williams SM (2017) Transdisciplinary approaches enhance the production of translational knowledge. Transl Res 182:123–134. https://doi.org/10.1016/j.trsl.2016.11.002

Cumming GS, Cumming DH, Redman CL (2006) Scale mismatches in social–ecological systems: causes, consequences, and solutions. Ecol Soc 11(1):14. https://www.ecologyandsociety.org/vol11/iss1/art14/

Darbellay F (2015) Rethinking inter- and transdisciplinarity: undisciplined knowledge and the emergence of a new thought style. Futures 65:163–174. https://doi.org/10.1016/j.futures.2014.10.009

Davies SW, Putnam HM, Ainsworth T, Baum JK, Bove CB, Crosby SC, Côté IM, Duplouy A, Fulweiler RW, Griffin AJ, Hanley TC, Hill T, Humanes A, Mangubhai S, Metaxas A, Parker LM, Rivera HE, Silbiger NJ, Smith NS, Spalding AK, Traylor-Knowles N, Weigel BL, Wright RM, Bates AE (2021) Promoting inclusive metrics of success and impact to dismantle a discriminatory reward system in science. PLoS Biol 19(6):e3001282. https://doi.org/10.1371/journal.pbio.3001282

Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Báldi A, Bartuska A, Baste IA, Bilgin A, Brondizio E, Chan KMA, Figueroa VE, Duraiappah A, Fischer M, Hill R, Koetz T, Leadley P, Lyver P, Mace GM, Martin-Lopez B, Okumura M, Pacheco D, Pascual U, Pérez ES, Reyers B, Roth E, Saito O, Scholes RJ, Sharma N, Tallis H, Thaman R, Watson R, Yahara T, Hamid ZA, Akosim C, Al-Hafedh Y, Allahverdiyev R, Amankwah E, Asah ST, Asfaw Z, Bartus G, Brooks LA, Caillaux J, Dalle G, Darnaedi D, Driver A, Erpul G, Escobar-Eyzaguirre P, Failler P, Fouda AMM, Fu B, Gundimeda H, Hashimoto S, Homer F, Lavorel S, Lichtenstein G, Mala WA, Mandivenyi W, Matczak P, Mbizvo C, Mehrdadi M, Metzger JP, Mikissa JB, Moller H, Mooney HA, Mumby P, Nagendra H, Nesshover C, Oteng-Yeboah AA, Pataki G, Roué M, Rubis J, Schultz M, Smith P, Sumaila R, Takeuchi K, Thomas S, Verma M, Yeo-Chang Y, Zlatanova D (2015) The IPBES Conceptual framework—connecting nature and people. Curr Opin Environ Sustain 14:1–16. https://doi.org/10.1016/j.cosust.2014.11.002

Díaz-Reviriego I, Turnhout E, Beck S (2019) Participation and inclusiveness in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Nat Sustain 2(6):457–464. https://doi.org/10.1038/s41893-019-0290-6

Dicks L, Haddaway N, Hernández-Morcillo M, Mattsson B, Randall N, Failler P, Ferretti J, Livoreil B, Saarikoski H, Santamaria L (2017) Knowledge synthesis for environmental decisions: an evaluation of existing methods, and guidance for their selection, use and development: a report from the EKLIPSE project. https://www.eklipse-mechanism.eu/apps/Eklipse_data/website/EKLIPSE_D3-1-Report_FINAL_WithCovers_V6.pdf

Dirnböck T, Bezák P, Dullinger S, Haberl H, Lotze-Campen H, Mirtl M, Peterseil J, Redpath S, Singh SJ, Travis J, Wijdeven SMJ (2013) Critical scales for long-term socio-ecological biodiversity research. In: Singh SJ, Haberl H, Chertow M, Mirtl M, Schmid M (eds) Long term socio-ecological research: studies in society-nature interactions across spatial and temporal scales. Springer, Netherlands, Dordrecht, pp 123–138. https://doi.org/10.1007/978-94-007-1177-8_6

Dorninger C, Abson DJ, Apetrei CI, Derwort P, Ives CD, Klaniecki K, Lam DPM, Langsenlehner M, Riechers M, Spittler N, von Wehrden H (2020) Leverage points for sustainability transformation: a review on interventions in food and energy systems. Ecol Econ 171:106570. https://doi.org/10.1016/j.ecolecon.2019.106570

Folke C, Pritchard L, Berkes F, Colding J, Svedin U (2007) The problem of fit between ecosystems and institutions: ten years later. Ecol Soc 12(1):1-38. http://www.jstor.org/stable/26267849

Fox HE, Caroline C, Nordby JC, Oliver RWP, Peterson GD, Pyke CR (2006) Perceived barriers to integrating social science and conservation. Conserv Biol 20(6):1817–1820. http://www.jstor.org/stable/4124711

Freeth R, Caniglia G (2020) Learning to collaborate while collaborating: advancing interdisciplinary sustainability research. Sustain Sci 15(1):247–261. https://doi.org/10.1007/s11625-019-00701-z

Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31(8):1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Gibson CC, Ostrom E, Ahn T-K (2000) The concept of scale and the human dimensions of global change: a survey. Ecol Econ 32(2):217–239. https://doi.org/10.1016/S0921-8009(99)00092-0

Goodchild MF (2011) Scale in GIS: an overview. Geomorphology 130(1):5–9. https://doi.org/10.1016/j.geomorph.2010.10.004

Gordon I, Bawa K, Bammer G, Boone C, Dunne J, Hart D, Hellmann J, Miller A, New M, Ometto J (2019) Forging future organizational leaders for sustainability science. Nat Sustain 2(8):647–649. https://doi.org/10.1038/s41893-019-0357-4

Haider LJ, Hentati-Sundberg J, Giusti M, Goodness J, Hamann M, Masterson VA, Meacham M, Merrie A, Ospina D, Schill C, Sinare H (2018) The undisciplinary journey: early-career perspectives in sustainability science. Sustain Sci 13(1):191–204. https://doi.org/10.1007/s11625-017-0445-1

Hay GJ (2005) Bridging scales and epistemologies: an introduction. Int J Appl Earth Obs Geoinf 7(4):249–252. https://doi.org/10.1016/j.jag.2005.06.004

Hernández-Morcillo M, Burgess P, Mirck J, Pantera A, Plieninger T (2018) Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. Environ Sci Policy 80:44–52. https://doi.org/10.1016/j.envsci.2017.11.013

Hernaus T, Černe M (2021) Becoming an organizational scholar. Navigating the Academic Odyssey. Edward Elgar Publishing Limited, Cheltenham. https://doi.org/10.4337/9781839102073

Hill R, Díaz S, Pascual U, Stenseke M, Molnár Z, Van Velden J (2021) Nature's contributions to people: weaving plural perspectives. One Earth 4(7):910–915. https://doi.org/10.1016/j.oneear.2021.06.009

Howitt R (1993) "A world in a grain of sand": towards a reconceptualisation of geographical scale. Aust Geogr 24(1):33–44. https://doi.org/10.1080/00049189308703076

Howitt R (1998) Scale as relation: musical metaphors of geographical scale. Area 30(1):49–58. https://doi.org/10.1111/j.1475-4762.1998.tb00047.x

Jessop B, Brenner N, Jones M (2008) Theorizing sociospatial relations. Environ Plan D: Soc Space 26(3):389–401. https://doi.org/10.1068/d9107

Jones S (2002) Social constructionism and the environment: through the quagmire. Glob Environ Change 12(4):247–251. https://doi.org/10.1016/S0959-3780(02)00062-6

Manson SM (2008) Does scale exist? An epistemological scale continuum for complex human–environment systems. Geoforum 39(2):776–788. https://doi.org/10.1016/j.geoforum.2006.09.010

Marston SA (2000) The social construction of scale. Prog Hum Geogr 24(2):219–242. https://doi.org/10.1191/030913200674086272

Marston SA, Jones JP, Woodward K (2005) Human geography without scale. Trans Inst Br Geogr 30(4):416–432. https://doi.org/10.1111/j.1475-5661.2005.00180.x

Meadows DH (1999) Leverage points: places to intervene in a system. https://www.conservationgateway.org/ConservationPlanning/cbd/guidance-document/key-advances/Documents/Meadows_Places_to_Intervene.pdf. Accessed 12 Jan 2023

Meyfroidt P, de Bremond A, Ryan CM, Archer E, Aspinall R, Chhabra A, Camara G, Corbera E, DeFries R, Díaz S, Dong J, Ellis EC, Erb K-H, Fisher JA, Garrett RD, Golubiewski NE, Grau HR, Grove JM, Haberl H, Heinimann A, Hostert P, Jobbágy EG, Kerr S, Kuemmerle T, Lambin EF, Lavorel S, Lele S, Mertz O, Messerli P, Metternicht G, Munroe DK, Nagendra H, Nielsen JØ, Ojima DS, Parker DC, Pascual U, Porter JR, Ramankutty N, Reenberg A, Roy Chowdhury R, Seto KC, Seufert V, Shibata H, Thomson A, Turner BL, Urabe J, Veldkamp T, Verburg PH, Zeleke G, zu Ermgassen EKHJ (2022) Ten facts about land systems for sustainability. Proc Natl Acad Sci 119(7):e2109217118. https://doi.org/10.1073/pnas.2109217118

Miller TR, Baird TD, Littlefield CM, Kofinas G, Chapin FS, Redman CL (2008) Epistemological pluralism: reorganizing interdisciplinary research. Ecol Soc 13(2):1-18. http://www.jstor.org/stable/26268006

Moon M, Richardson AD, Friedl MA (2021) Multiscale assessment of land surface phenology from harmonized Landsat 8 and Sentinel-2, PlanetScope, and PhenoCam imagery. Remote Sens Environ 266:112716. https://doi.org/10.1016/j.rse.2021.112716

Moore A (2008) Rethinking scale as a geographical category: from analysis to practice. Prog Hum Geogr 32(2):203–225. https://doi.org/10.1177/0309132507087647

Moran EF, Lopez MC (2016) Future directions in human–environment research. Environ Res 144(Part B):1–7. https://doi.org/10.1016/j.envres.2015.09.019

Moss T, Newig J (2010) Multilevel water governance and problems of scale: setting the stage for a broader debate. Environ Manag 46(1):1–6. http://download.springer.com/static/pdf/461/art%253A10.1007%252Fs00267-010-9531-1.pdf?originUrl=http%3A%2F%2Flink.springer.com%2Farticle%2F10.1007%2Fs00267-010-9531-1&token2=exp=1488900657~acl=%2Fstatic%2Fpdf%2F461%2Fart%25253A10.1007%25252Fs00267-010-9531-1.pdf%3ForiginUrl%3Dhttp%253A%252F%252Flink.springer.com%252Farticle%252F10.1007%252Fs00267-010-9531-1*~hmac=e29c7892c5bddf9c479a77ad757e6ff6a89ef699eb7cb0ec6d7c4ec28f850ae4

Mountz A, Bonds A, Mansfield B, Loyd J, Hyndman J, Walton-Roberts M, Basu R, Whitson R, Hawkins R, Hamilton T (2015) For slow scholarship: a feminist politics of resistance through collective action in the neoliberal university. ACME Int J Crit Geogr 14(4):1235–1259. https://acme-journal.org/index.php/acme/article/view/1058/1141

Neumann RP (2009) Political ecology: theorizing scale. Prog Hum Geogr 33(3):398–406. https://doi.org/10.1177/0309132508096353

Newig J, Moss T (2017) Scale in environmental governance: moving from concepts and cases to consolidation. J Environ Plan Policy Manag 19(5):473–479. https://doi.org/10.1080/1523908X.2017.1390926

Niewöhner J, Bruns A, Haberl H, Hostert P, Krueger T, Lauk C, Lutz J, Müller D, Nielsen JØ (2016) Land use competition: ecological, economic and social perspectives. In: Niewöhner J, Bruns A, Hostert P, Krueger T, Nielsen JØ, Haberl H, Lauk C, Lutz J, Müller D (eds) Land use competition: ecological, economic and social perspectives. Springer International Publishing, Cham, pp 1–17. https://doi.org/10.1007/978-3-319-33628-2_1

Paasche Ø, Österblom H (2019) Unsustainable science. One Earth 1(1):39–42. https://doi.org/10.1016/j.oneear.2019.08.011

Pereira LM, Davies KK, den Belder E, Ferrier S, Karlsson-Vinkhuyzen S, Kim H, Kuiper JJ, Okayasu S, Palomo MG, Pereira HM,

Peterson G, Sathyapalan J, Schoolenberg M, Alkemade R, Carvalho Ribeiro S, Greenaway A, Hauck J, King N, Lazarova T, Ravera F, Chettri N, Cheung WWL, Hendriks RJJ, Kolomytsev G, Leadley P, Metzger J-P, Ninan KN, Pichs R, Popp A, Rondinini C, Rosa I, van Vuuren D, Lundquist CJ (2020) Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. People Nat. https://doi.org/10.1002/pan3.10146

Plieninger T, Kohsaka R, Bieling C, Hashimoto S, Kamiyama C, Kizos T, Penker M, Kieninger P, Shaw BJ, Sioen GB (2018) Fostering biocultural diversity in landscapes through place-based food networks: a "solution scan" of European and Japanese models. Sustain Sci 13(1):219–233. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6086265/pdf/11625_2017_Article_455.pdf

Pullin AS, Sutherland W, Gardner T, Kapos V, Fa JE (2013) Conservation priorities: identifying need, taking action and evaluating success. Key Top Conserv Biol 2:3–22

Pulver S, Ulibarri N, Sobocinski KL, Alexander SM, Johnson ML, McCord PF, Dell'Angelo J (2018) Frontiers in socio-environmental research: components, connections, scale, and context. Ecol Soc 23(3). Article 23. https://doi.org/10.5751/ES-10280-230323

Reid WV (2006) Bridging scales and epistemologies in the Millennium Ecosystem Assesment. Bridging scales and epistemologies—linking local knowledge and global science in multi-scale assessments, Alexandria, Egypt

Reid WV, Berkes F, Wilbanks T, Capistrano D (eds) (2006) Bridging scales and knowledge systems. Concepts and applications in Ecosystem Assessment. Island Press, Washington

Rocha PLBd, Pardini R, Viana BF, El-Hani CN (2020) Fostering inter- and transdisciplinarity in discipline-oriented universities to improve sustainability science and practice. Sustain Sci 15(3):717–728. https://doi.org/10.1007/s11625-019-00761-1

Sayre NF (2005) Ecological and geographical scale: parallels and potential for integration. Prog Hum Geogr 29(3):276–290. https://doi.org/10.1191/0309132505ph546oa

Schneidewind U, Singer-Brodowski M, Augenstein K (2016) Transformative science for sustainability transitions. In: Brauch HG, Oswald Spring Ú, Grin J, Scheffran J (eds) Handbook on sustainability transition and sustainable peace. Springer International Publishing, Cham, pp 123–136. https://doi.org/10.1007/978-3-319-43884-9_5

Sellberg MM, Cockburn J, Holden PB, Lam DP (2021) Towards a caring transdisciplinary research practice: navigating science, society and self. Ecosyst People 17(1):292–305. https://doi.org/10.1080/26395916.2021.1931452

Semper-Pascual A, Decarre J, Baumann M, Camino M, Di Blanco Y, Gómez-Valencia B, Kuemmerle T (2020) Using occupancy models to assess the direct and indirect impacts of agricultural expansion on species' populations. Biodivers Conserv 29(13):3669–3688. https://doi.org/10.1007/s10531-020-02042-1

Singh SJ, Haberl H, Chertow M, Mirtl M, Schmid M (eds) (2012) Long term socio-ecological research: studies in society-nature interactions across spatial and temporal scales, vol 2. Springer Science & Business Media, Berlin. https://doi.org/10.1007/978-94-007-1177-8

Soininen N, Raymond CM, Tuomisto H, Ruotsalainen L, Thorén H, Horcea-Milcu A-I, Stojanovic M, Lehtinen S, Mazac R, Lamuela C, Korpelainen N, Vainio A, Toivanen R, McPhearson T, Nagatsu M (2022) Bridge over troubled water: managing compatibility and conflict among thought collectives in sustainability science. Sustain Sci 17(1):27–44. https://doi.org/10.1007/s11625-021-01068-w

Steel KM, Thompson H, Wright W (2019) Opportunities for intra-university collaborations in the new research environment. High Educ Res Dev 38(3):638–652. https://doi.org/10.1080/07294360.2018.1549537

Sutherland WJ, Gardner T, Bogich TL, Bradbury RB, Clothier B, Jonsson M, Kapos V, Lane SN, Möller I, Schroeder M (2014) Solution scanning as a key policy tool: identifying management interventions to help maintain and enhance regulating ecosystem services. Ecol Soc. https://doi.org/10.5751/ES-06082-190203

Swyngedouw E (2004) Scaled geographies: nature, place, and the politics of scale. In: Sheppard E, McMaster RB (eds) Scale and geographic inquiry: nature, society, and method. Blackwell Publishing Ltd., Hoboken, pp 129–153

Turner MG et al (1989) Predicting across scales: theory development and testing. Landscape Ecol 3(3):245–252. https://doi.org/10.1007/BF00131542

Veldkamp T, Polman N, Reinhard S, Slingerland M (2011) From scaling to governance of the land system: bridging ecological and economic perspectives. Ecol Soc 16(1):1

Verburg PH, Mertz O, Erb K-H, Haberl H, Wu W (2013) Land system change and food security: towards multi-scale land system solutions. Curr Opin Environ Sustain 5(5):494–502. https://doi.org/10.1016/j.cosust.2013.07.003

Villeneuve D, Durán-Rodas D, Ferri A, Kuttler T, Magelund J, Mögele M, Nitschke L, Servou E, Silva C (2020) What is interdisciplinarity in practice? Critical reflections on doing mobility research in an intended interdisciplinary doctoral research group. Sustainability 12(1):197. https://www.mdpi.com/2071-1050/12/1/197

Wada M, Grigorovich A, Fang ML, Sixsmith J, Kontos P (2020) An exploration of experiences of transdisciplinary research in aging and technology. Forum Qual Sozialforschung Forum Qual Soc Res. https://doi.org/10.17169/fqs-21.1.3332

Ware M, Mabe M (2015) The STM report: an overview of scientific and scholarly journal publishing. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1008&context=scholcom. Accessed 12 Jan 2023

Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, Blomberg N, Boiten J-W, da Silva Santos LB, Bourne PE, Bouwman J, Brookes AJ, Clark T, Crosas M, Dillo I, Dumon O, Edmunds S, Evelo CT, Finkers R, Gonzalez-Beltran A, Gray AJG, Groth P, Goble C, Grethe JS, Heringa J, 't Hoen PAC, Hooft R, Kuhn T, Kok R, Kok J, Lusher SJ, Martone ME, Mons A, Packer AL, Persson B, Rocca-Serra P, Roos M, van Schaik R, Sansone S-A, Schultes E, Sengstag T, Slater T, Strawn G, Swertz MA, Thompson M, van der Lei J, van Mulligen E, Velterop J, Waagmeester A, Wittenburg P, Wolstencroft K, Zhao J, Mons B (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3(1):160018. https://doi.org/10.1038/sdata.2016.18

Zhang J, Atkinson P, Goodchild MF (2014) Scale in spatial information and analysis. CRC Press Taylor & Francis Group, Boca Raton