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Bridging the knowledge-action gap: A framework for co-producing actionable knowledge

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ABSTRACT

Rapidly increasing knowledge on environmental problems and their potential solutions is underused by policy and practice. This mismatch constitutes a knowledge-action gap. To bridge the gap, the concept of actionable knowledge has been proposed, which is often understood as outputs, data, policy briefs, or other types of products. We instead propose to understand actionable knowledge as a process that has (1) cumulative and stepwise, (2) iterative and cyclical, and (3) coevolutionary characteristics. These characteristics are often considered in isolation or even to be in contradiction with each other. We integrate these three characteristics in an analysis of transdisciplinary project developing a catchment-scale land use roadmap and catchment coordination in the Kiiminkijoki river catchment, northern Finland. Our analysis is based on four general phases in a knowledge co-production process (making sense together, knowledge validation, usable outputs, boundary spanning), which are concretized through nine practical steps. We find that collection, analysis, and usage of the knowledge has been even more important for action than the final output (i.e., the roadmap). Furthermore, the process of actionable knowledge does not end with the project but continues with negotiations to establish a catchment coordinator position. Our major finding is that there is no single point in time during a transdisciplinary project to bridge the knowledge–action gap but multiple planned and surprising opportunities emerge during the process. Overall, our approach contributes to advance sustainability transformations in catchment management and governance by understanding how transdisciplinary projects can initiate and are a part of evolving knowledge-action processes.

1. Introduction

Scientific knowledge increases rapidly to generate responses to environmental problems such as climate change and biodiversity loss. However, the growing pools of knowledge are underused by decision-makers and policy (e.g. Ripple et al., 2017; IPBES, 2019; GBO 5, 2020; Lee et al., 2023) highlighting a knowledge–action gap (Van Kerkhoff and Lebel, 2006; Wiek et al., 2012; Cook et al., 2013; Clark and Harley, 2020). The gap is manifested as a lack of evidence-based policy, and a lack of integration of policy-relevant questions with the ongoing research (Jagannathan et al., 2023).

One effort to bridge the gap is the development of actionable

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knowledge, which can catalyze sustainability transformations (Caniglia et al., 2021; Hölscher et al., 2023). Actionable knowledge can be considered "not only relevant to the world of practice, but it is the knowledge that people use to create the world" (Argyris, 1993). The concept refers commonly to scientific outputs such as data, tools, findings and articles, which can inform policy and action (Arnott, 2019; Nyboer et al., 2021). This corresponds with the characteristics of a linear science-policy-society interaction model, where the key rationale is to produce high quality outputs and push them to activate policy, for example by dissemination efforts. Furthermore, it has been proposed that the problems related to bridging knowledge and action are linked to the availability, interpretability, and usability of knowledge (Roche et al., 2022). Therefore, this common view focuses on the quality of the outputs.

However, there are also process-based definitions on actionable knowledge. Cash et al. (2003) highlight legitimacy, credibility and relevance as key attributes for improving the use of knowledge by societal actors, which can be enhanced by co-production approaches. Roux et al. (2006) along with Stern et al. (2021) address that knowledge should not be interpreted as an exchangeable thing but rather as a process of interaction among diverse actors across a science-society landscape. While these ideas emphasize the importance of co-production, they tend to regard it as a means to create better outputs. We suggest that actionable knowledge extends beyond the outputs. Outputs are not the only way to generate action; instead, action can be generated at any phase of the knowledge co-production process, also beyond the temporal scope of projects utilizing these approaches.

Co-production processes from knowledge to action have been formalized and enacted especially by established science-policy interfaces with detailed guidelines for the assessment of co-production processes (e.g. IPBES, 2018). In transdisciplinary studies, the process to bridge the knowledge–action gap has been considered from at least three perspectives. Firstly, the cumulative knowledge-first approach contains a process starting from co-learning, proceeding via reflection to the actual conduct of research and leading finally to the implementation of the findings (Pineo et al., 2021). Secondly, the process to create actionable knowledge has been emphasized as being iterative, cyclical, and interactive leading to address societal challenges and to redefine research problems (Jahn et al., 2012; Hoffmann et al., 2019). Thirdly, the process from knowledge to action has been considered to be defined by "co-production of science and social order" (Jasanoff, 2004) that takes place in complex webs of actors who produce and use knowledge (Klenk, 2018; Sarkki et al., 2020). We refer to this process as coevolution of knowledge and action (see Chapman and Schott, 2020). These three approaches are often considered in isolation from each other (e.g. Hölscher et al., 2023). Through our case study, we propose that these three types of approaches are not mutually exclusive but take place simultaneously.

We examine actionable knowledge through a case study, which considers a transdisciplinary project seeking to identify, test, and advance sustainable land use solutions in the Kiiminkijoki river catchment, northern Finland. The project brings together a group of researchers including social and natural scientists as well as local and administrative actors into a knowledge co-production process. We document and analyze the process of developing a land use roadmap in the catchment and establishing a catchment coordinator position. Our aims are to (1) provide conceptual background for understanding cumulative, iterative and coevolutionary approaches on actionable knowledge, (2) analyze actionable knowledge co-production in a transdisciplinary process, and (3) propose an actionable knowledge framework that integrates the cumulative, iterative and coevolutionary approaches.

The initial objective of the project and the related process was to develop a land use sector plan for carbon storage and sequestration, partly due to the funding instrument (Catch the Carbon Program of the Ministry of Agriculture and Forestry of Finland). Climate solutions on drained peatlands are a key target in Finnish land use because the drainage has increased peat decomposition and carbon dioxide emissions to the atmosphere (Maljanen et al., 2010, Alm et al., 2023). However, as we detail in the following sections, the objective was reformulated during the process due to multiple reasons.

2. Actionable knowledge as a cumulative, iterative, and coevolutionary process

Literature on actionable knowledge examines processes, practices, and pathways by which knowledge informs action. Furthermore, it aims to understand and catalyze transitions in scientific knowledge production and use (Arnott et al., 2020, Jagannathan et al., 2023). In some conceptualizations of actionable knowledge, importance of both knowledge and processes to produce it are recognized; for instance, according to Mach et al. (2020), actionable knowledge consists of substantive interactions, equitable relationships, and usable knowledge. Some other conceptualizations emphasize knowledge co-production processes engaging with the realms of policy and practice, which rely either on knowledge-first or process-oriented approaches (e.g., Hölscher et al., 2023). Moreover, knowledge, policy, and practice can also be seen tightly interlinked in ways that are hard to predict or even fully understand (see Jasanoff, 2004). We call this a coevolutionary view on knowledge and action. These three approaches can be used to summarize actionable knowledge co-production as 1) cumulative, 2) cyclical and iterative, and 3) coevolutionary (Fig. 1).

2.1. Actionable knowledge as a cumulative process of co-production

The cumulative process of actionable knowledge co-production can be divided into four phases, elaborated in the following subsections. The rationale in this approach is to cumulate knowledge towards catalyzing action.

2.1.1. Making sense together

The first phase relates to knowledge co-production between diverse actors. It has been occasionally called "making sense together", as opposed to the linear model of science-policy-society interactions characterized by "speaking truth to power" (Hoppe, 1999). While literature on knowledge co-production includes various conceptualizations (e.g., Turnhout et al., 2020, Norström et al., 2020), we consider that the process starts with defining a problem. This is crucial, as without a conceptualization of the problem, it is difficult to select the relevant stakeholders to be invited into knowledge co-production that is context-based, pluralistic, goal-oriented, and interactive (Norström et al., 2020). Shared problem definition helps also to increase trust between the partners to work for the same goal. Following the classical works of Luhmann (1979) and Putnam (2000), personal trust begins from learning familiarity with others, which leads to the predictability of others' behavior but also involves expectations on the integrity, honesty and moral character of the trusted and the balancing of self-interest.

2.1.2. Validation

The second phase is the validation of knowledge production. In science, peer review is heralded as a distinguishing feature that makes scientific knowledge categorically different from other types of knowledge (Tennant and Ross-Hellauer, 2020). However, with the case of actionable knowledge, the knowledge producers are not only scientists but also societal actors. In addition to the knowledge claims made during knowledge production, the applicability of the knowledge is of crucial importance.

Societal validation of scientific knowledge acts as feedback to the researchers as regards to the knowledge they produce. Societal validation of scientific knowledge has been discussed at least since the 1990s with ideas of socially robust knowledge (Nowotny, 2003) and extended

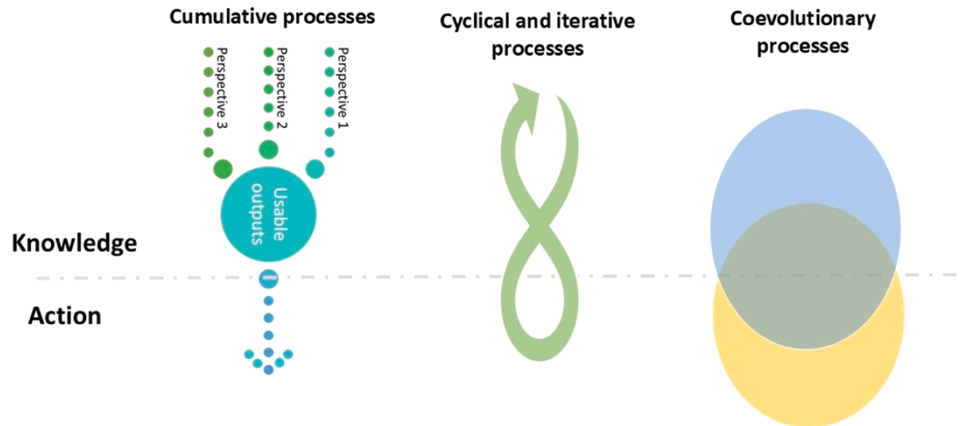

Fig. 1. Three types of processes associated with actionable knowledge co-production. Cumulative approach considers knowledge and action as fundamentally separate domains, and that knowledge cumulates through subsequent phases leading ultimately to changing action. This approach prioritizes knowledge. Cyclical approach recognizes iterative development and feedback across phases in knowledge co-production and between evolving action and knowledge co-production. This approach prioritizes process. Coevolutionary approach considers that knowledge and action are hard to distinguish from each other and that they coevolve through complex interactions. This approach prioritizes understanding complexity and emergent connections between knowledge and action.

peer review where also non-scientists can evaluate the knowledge, truth claims, and applicability (Funtowicz and Ravetz, 1990). We consider that the societal validation of the actionability of the knowledge can be done in two ways. Firstly, by experimenting with the knowledge in practical situations, for example by pilot projects or policy experiments (e.g., Martin and Sanderson, 1999). Secondly, it can be validated by discussing its societal and practical relevance with stakeholders. This includes participatory impact assessments, such as multicriteria decision analysis (e.g., Marttunen et al., 2015), where scientific knowledge is elaborated and extended by stakeholders' views. After the elaboration, the knowledge on the anticipated impacts and their desirability by the stakeholders can be discussed to validate the stakeholder perspectives, impacts on various issues and the relevance of the knowledge itself.

2.1.3. Usable outputs

When the knowledge co-production processes have taken place and knowledge has been scientifically and societally validated, concrete outputs come into play. While the phase of usable outputs can be considered as the key for the push of knowledge by science to society, it is also a necessary phase for knowledge co-production and validation. Even if the actionable knowledge is in our view rather a process than a stable output, the results of the knowledge co-production and validation need to be reported in an accessible and usable format. It has been highlighted that relevant, legitimate and credible knowledge will be more likely to be used in policy (Cash et al., 2003), but overall, there are several criteria and definitions for usable knowledge (Dilling and Lemos, 2011, Clark et al., 2016, Nguyen et al., 2019).

We consider that actionability of the outputs depend on the process preceding the outputs, related to for example transparency of the process, integration of multiple knowledge systems, a holistic approach, and transdisciplinary aspects, but the output itself can also be actionable based on its characteristics, related for instance to its action, solution, and future-orientation. These criteria can be satisfied with target-seeking scenarios such as backcasting (Robinson, 2003) and roadmaps (e.g., Rockström et al., 2017). Both include phase-wise pathways from the current situation towards co-defined desirable futures and often include identification of actor-based actions as well as potential obstacles, and ways to overcome them towards the desirable future. As such, the outputs are explicitly connected to the realm of practice and include recommendations for practical actions.

2.1.4. Boundary spanning

It is not enough to produce or even co-produce knowledge and make it available for policy makers and societal actors, but its use needs to be catalyzed in some way. For example, the Global Biodiversity Assessment (Heywood and Watson, 1995) was done by well-known scientists, but it had almost no policy impacts because of the lack of outreach during and after knowledge production. Thus, tackling sustainability challenges requires individuals who can work across the realms of science, policy, and society (Arnott et al., 2020). While there are several ways and concepts to think about this, including knowledge brokerage (Pielke Jr, 2007), networking, and meshworking (Klenk, 2018), we focus here on boundary spanning.

The boundary spanning concept has roots in business and organizational management literature where the concept has been designed to identify the roles and functions that facilitate knowledge exchange between organizations (Aldrich and Herker, 1977, Bednarek et al., 2018). It has also been used for example to understand science-policy relations in a sustainability context (Bednarek et al., 2018). Boundary spanning can enable knowledge exchange between science and policy, thus actively shaping the complex science-policy landscapes (Posner and Cvitanovic, 2019).

While there are many definitions of boundary spanning, following Bednarek et al. (2018) and Posner and Cvitanovic (2019), we refer it to enable the exchange between knowledge production and its use to support evidence-informed decision-making, while the process is actively and explicitly facilitated by boundary spanners. In other words, the spanners help to tailor knowledge for decision-making, facilitate the decision-making processes, enhance societal and policy acceptance of scientific knowledge, and seize emerging opportunities to inform policy (Bednarek et al., 2018).

2.2. Actionable knowledge as iterative and cyclical process

Transdisciplinarity includes phases of scientific and societal problem formulation, discourses and practices. These are integrated through a formation of a common problem, co-production of new knowledge, and evaluation of new knowledge regarding its scientific and societal relevance (Jahn et al., 2012). Building from this, Hoffmann et al. (2019) propose five phases for transdisciplinary projects: (i) defining sustainability problems, (ii) producing new knowledge, (iii) assessing the new knowledge, (iv) disseminating the new knowledge in the realms of both science and practice, and (v) using the new knowledge in both realms. Important in these conceptualizations is that they emphasize the iterative, interactive, and cyclical nature of transdisciplinary processes, where the phases of the process may be in different orders and where there is feedback between the phases.

We also emphasize iterative feedback between the diverse phases within the project scope and in a longer term between different subsequent projects on the same topic. Feedback within a project includes the possibility to reflect and redefine the initial problem statement. This requires not only listening to the stakeholders' plural perspectives but also to respond to these perspectives by reformulating scientific ideas or approaches. In some cases, the redefined problem may lead to new processes with additional stakeholders and different concepts.

2.3. Coevolution of knowledge and action

The third approach of actionable knowledge co-production is coevolution which can be defined as interlinked development of two or more realms in a way that the development trajectories become difficult to separate from each other. Following the coevolutionary approach, the actionability of knowledge is affected not only by how it is co-produced, formulated, and disseminated, but also by how it fits to the agendas, purposes, and strategies of the actors who utilize it and transform it into action. This implies that the relations of knowledge and action are highly complex and difficult to anticipate (Klenk, 2018; Sarkki et al., 2020). Therefore, knowledge cannot only generate action, but its production is affected by action; in other words, knowledge and action are co-constituted and difficult to distinguish from one another. Jasanoff (2004) shows "how scientific knowledge both embeds and is embedded in social identities, institutions, representations and discourses".

3. Materials and methods

3.1. Kiiminkijoki river catchment

The Kiiminkijoki river catchment spans 3824 km^2 in the northern Finland (Fig. 2) and its population consists of ca. 25,000 inhabitants. The catchment is located within four municipalities in the North Ostrobothnia and Kainuu regions. Approximately 30 % of the basin is on state-owned lands which are concentrated on the upstream eastern part. In the downstream, most of the land is owned by private landowners with typically relatively small estates.

The river is of regional and national importance due to it being one of the rare free-flowing rivers in Finland. The river itself and all its tributaries are protected by the EU Natura 2000 network. Additionally, there are also other notable nature protection areas in the catchment such as the Olvassuo Nature Reserve. In total, the nature protection sites cover ca. 15 % of the area.

Despite its conservation status and rurality, the water quality in the river system ranges between poor in some of the tributaries to excellent in the upstream part of the mainstream. The water quality has deteriorated because of intensive peatland drainage, forestry, and peat production during the latter half of the 20th century, while the water quality has slowly improved in the 21st century. The impaired water quality led to the disappearance of salmon and other migratory fish which were a subject of local pride and livelihood until the latter part of 20th century. A key future hope for the locals is a return of salmon (Sarkki et al., 2024).

Kiiminkijoki presents a unique case for catchment governance due to its large areal extent, regional importance, multiple stakeholders, scattered land tenure, and multiple administrative units. The governance of the catchment also needs to account for multiple environmental and social targets. In addition to local hopes related to salmon and water quality, these include e.g., global, national, and regional environmental policies related to climate change mitigation, peatland management, biodiversity restoration and conservation, and water quality management, as well as needs for local livelihood opportunities and a demand for forest biomass and renewable energy.

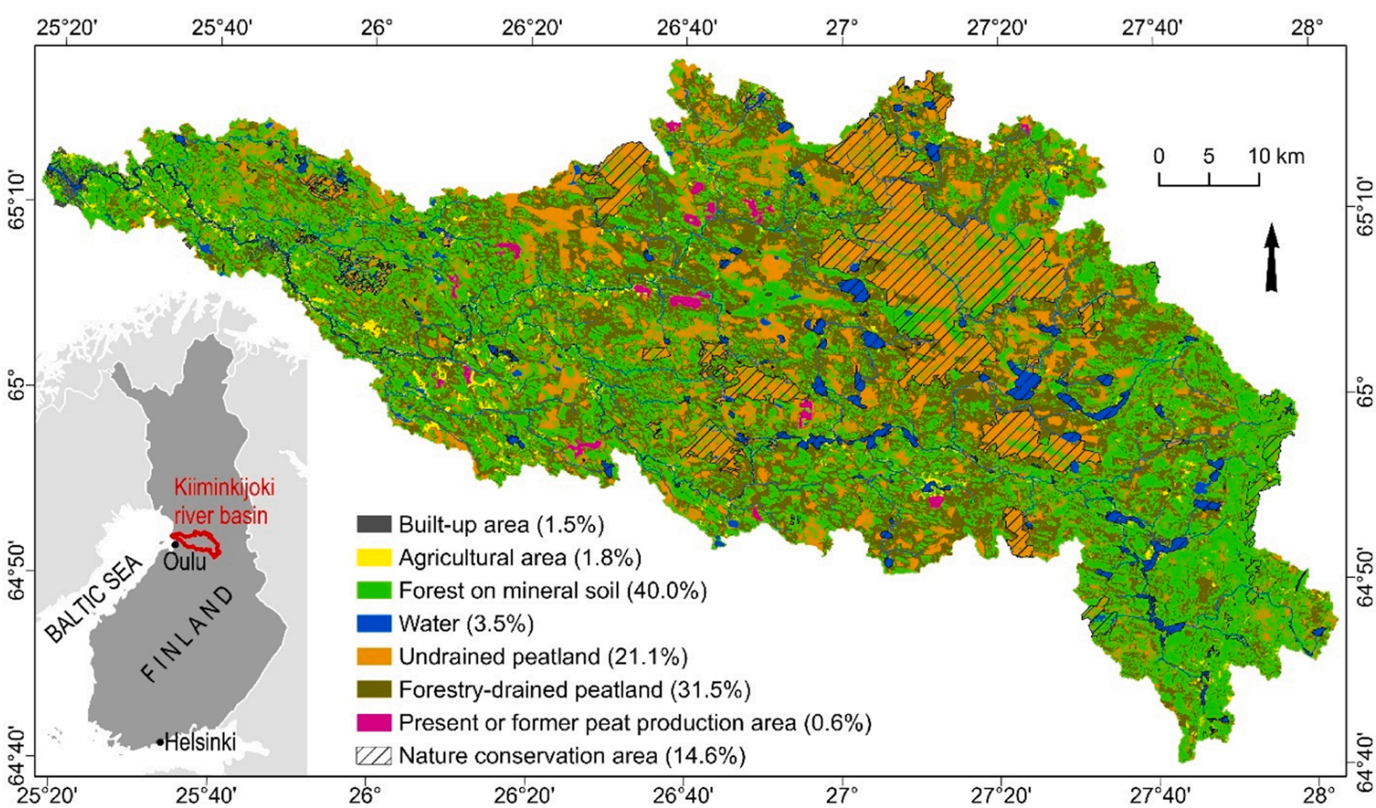

Fig. 2. Land use/land cover in the 3824 km2 Kiiminkijoki river basin in northern Finland. Data sources: Finnish Environment Institute (Corine Land Cover, peatland drainage status, conservation areas), ELY Centre for North Ostrobothnia (peat production areas), and Finnish Food Authority (land parcel register). Redrawn from Sarkki et al. (2024) (Creative Commons Attribution 4.0 International License, http://creativecommons.org/licenses/by/4.0/).

3.2. Nine-step approach for land use roadmap and catchment coordination

We constructed a nine-step approach to develop a land use roadmap to steer a desired change in the catchment (Table 1). In each step, a variety of data collection and analysis methods were used, spanning social and natural sciences and qualitative and quantitative methods.

Each of the steps can be related to one of the phases of the cumulative approach on actionable knowledge co-production (Section 2.1). Following backcasting (Robinson, 2003) logic, after problem definition and background knowledge collection (Steps 1–3), future visioning (Step 5) was followed by the selection of land use and other measures with which the visions can be achieved (Steps 6–8). The phases did not progress linearly but iteratively, as validation (Phase 2) of knowledge was started already early on the process by piloting land use and restoration measures (Step 4). This was done to motivate stakeholders to participate and to exemplify what kinds of measures can be included in the final roadmap that was initially planned to be the last step in the process (Step 8, Phase 3).

After the first interviews and workshops (Steps 3 and 5), it became evident that the current governance and co-operation structures are ill-suited to enable land use and other changes in the catchment; therefore, changes in catchment governance, stakeholder interaction, administrative co-operation, and society-at-large were also needed. Hence, in addition to producing the roadmap (Step 8), we started to pave a way for a catchment coordinator to coordinate the restoration measures, enhance knowledge co-production, and interact with the various stakeholders, including motivation of landowners and co-operation with the administrative, civil society and private sector actors. This final Step 9 concurs with the boundary spanning aspects (Phase 4).

Key stakeholders included administrative actors, civil society, interest groups, and key landowners. Stakeholders were chosen based on three main criteria: (1) interest towards the Kiiminkijoki river catchment (e.g., civil society organizations such as the Kiiminkijoki River Association and nature protection associations), (2) power to make decisions about the catchment (e.g., municipalities, large landowners, forest associations), and (3) knowledge about the catchment (e.g., Kiiminkijoki River Association, landowners and land users in the catchment) or catchment planning in general (e.g., research organizations, regional administration). We listed the stakeholders with the help of existing knowledge of the area, by conducting Internet searches and by snowballing via existing contacts, and contacted them via email, phone, local events, and workshop invitations. The involved stakeholders had in general an interest in environmental questions. Stakeholders emphasizing economic profits were largely underrepresented because of the chosen criteria and their lack of interest to participate.

We employed reflective and collaborative autoethnography (Chang et al., 2013) as our main method. Reflection among the researchers in transdisciplinary projects has been considered important to harness impact and to adjust project dynamics to emerging situations (Pohl et al., 2017). Collaborative autoethnography has been used to analyze transdisciplinary projects at the science-policy intersection (von Seggern et al., 2023) and to bridge natural and social science divide (Haeffner et al., 2022). Overall, a need for self-reflectivity in transdisciplinary and transformative research has been clearly voiced (Schneider et al., 2019, Bergmann et al., 2021). We acknowledge that the used collaborative autoethnography method has its caveats: the results are based on our collective experiences, and we are not in an objective position to analyze the outputs and the process (von Seggern et al., 2023); however, it has been argued that bias is always present in science and collaborative autoethnography may help to observe and deal with that bias (Haeffner et al., 2022). We managed the evident bias by collectively discussing and reflecting our position as researchers in guiding and reporting the process, by focusing to report the informant perceptions, and by elaborating which steps and results are based on our reasoning and which on stakeholders' views.

Table 1
A nine-step approach for constructing the land use roadmap and establishing a catchment coordination in the Kiiminkijoki river catchment. The phases are elaborated in Section 2.1.

Step (What)	Target (Why)	Methods (How)	Phase
1 Problem definition	To screen what hinders the achievement of the environmental and social targets in the catchment	Writing a project application and starting the project, collecting initial information about the development needs from the key stakeholders	1 Making sense together
2 Identification of stakeholders	To identify stakeholders that should be included in the roadmap building	Desktop stakeholder analysis and listing of potential stakeholders	1 Making sense together
3 Collection of background information	To collect information from relevant stakeholders about future hopes and concerns; to gather information about the catchment	a) Half-day onsite/ online kickoff stakeholder meeting (N=35) on April 25, 2022; interviews of local stakeholders (N=41), sampled with purposeful (Step 2) and snowball sampling; organization of a half-day onsite focus group discussion with forest-owners (N=7) on October 18, 2022; a quantitative questionnaire targeted to stakeholders and local residents (35 responses); participatory observation in local events. The meetings and questionnaire are described in more detail in Sarkki et al. (2024). b) Collection and exploratory analysis of GIS and other environmental data about water quality, land use and land cover, and forestry and agricultural practices in the catchment.	1 Making sense together
4 Piloting land use and restoration measures	To test the implementation of restoration measures; to motivate local stakeholders to the process	Participatory mapping of areas needing restoration in the kickoff meeting (Step 3) and in another half-day onsite local workshop (N=10), planning and implementation of the restoration measures.	2 Validation of knowledge production
5 Visioning desirable futures and listing of development needs	To bring stakeholders together and vision desired and alternative futures; to plan possible land use measures, to provide opinions on what kind of impact assessment should be	A one-day onsite participatory workshop with 23 participants identified in the Step 2 (with part of them interviewed in the Step 3) on February 6, 2023 (Sarkki et al., 2024). The workshop	1 Making sense together

(continued on next page)

Table 1 (*continued*)

Step (What)	Target (Why)	Methods (How)	Phase
	conducted in the Step 6	included result presentations from the Steps 3–4, small group (7–8 participants in each group) exercises about future visions and steps needed to take to reach the desirable futures, and discussions about what to be included in the impact assessment in the Step 6.	
6 Assessing the impacts of potential land use measures	To analyze the environmental and social impacts of planned land use measures	Forestry simulations with the Monsu forest planning software (Pukkala, 2011) of the potential environmental and economic impacts of forestry and water protection measures (Nieminen et al., 2024), GIS analyses of agricultural peatlands suitable for rewetting and other agricultural measures, collection of existing knowledge about peatland restoration and after-use of peat extraction sites. Interviews of local stakeholders about social acceptability and justice related to the land use measures (N=41; same as in the Step 3). A synthesis of the results is provided in Räsänen et al. (2024a).	2 Validation of knowledge production
7 Discussing the impact assessment results	To discuss the impact assessment results and choose the measures to be included in the roadmap	A one-day onsite participatory workshop with 26 participants on January 12, 2024. The workshop included presentations of the Step 6 results, small group (6–7 participants in each group) discussion of what targets as well as land use and governance measures should be included in the roadmap.	2 Validation of knowledge production
8 Synthesizing the land use roadmap	To write and finalize the roadmap and motivate the stakeholders to implement it	After the Step 7 workshop, feedback on the roadmap sketch was collected with a survey (10 responses, 42 % response rate). A one-day onsite participatory workshop with 18 participants on April 8, 2024. The workshop included small group (6 participants in each group) discussions about the roadmap contents, including vision, targets, land use and other measures, responsible actors, and roadmap marketing and implementation. After the workshop, the roadmap was edited and a final feedback round was held (N=4), after which the final version was prepared and published (Räsänen et al., 2024b).	3 Usable outputs
9 Establishing a catchment coordinator	To develop a coordination structure to implement the roadmap and catchment governance	Three virtual 60–120 min group discussions (October 10, November 30, December 12, 2023), grant application writing for a catchment coordination project, which was funded in September 2024.	4 Boundary spanning

As research material, we used resources collected during the process including the initial project proposal, transcribed interviews, notes taken in workshops and project meetings, written reports and publications (Räsänen et al., 2024a; Sarkki et al., 2024; Nieminen et al., 2024; Räsänen et al., 2024b), and other data collected (Table 1). Together, these materials enabled us to use abductive reasoning (Timmermans and Tavory, 2012) to construct the process description of the nine steps that happened in the project.

4. Results

In this section, we report the key results of the nine-step approach (Table 2) and link them to the four phases (Section 2.1) which partly overlapped in time (Fig. 3). Concurrently, we report how the forms of actionable knowledge evolved throughout the whole process.

4.1. Making sense together

The Phase 1 (Making sense together) consisted of the Steps 1–3 and 5. During the Step 1, the research plan for the project was written and the process was centered on climate change mitigation as it was the key focus in the funding program and because of the urgency of climate actions. During the Step 2, stakeholders (Table 2) were identified based on the criteria described in the Section 3.2 and contacted. Their views on the catchment development were inquired during the Step 3. While most of the stakeholders were identified in early 2022 and interviewed during 2022, the work continued until late 2023.

During the Step 3, it became clear that even though climate actions were considered important, many stakeholders emphasized water quality and positive changes in the local environment instead of the more distant (inter)national climate and biodiversity targets as well as economic benefits of large industrial actors. Moreover, the usefulness of land use measures focusing solely on climate change mitigation was doubted due to the uncertainty in their impact assessment and possible

Table 2
A summary of key results from each of the nine steps of the nine-step approach (see Table 1).

Step	Key results
1 Problem definition	– We identified a need to develop blueprint approaches for how to account for multiple environmental and social targets in large catchment areas with multiple stakeholders and fragmented landownership. – A key gap was linked to the local actors' limited knowledge of what kind of measures should be conducted and how the measures should be spatially allocated.
2 Identification of stakeholders	– Key stakeholders included regional and local administrations, multiple civil society organizations such as the Kiiminkijoki River Association, large landowners (state, forestry companies), forest associations, research organizations, interest groups related especially to nature protection, forestry, and agriculture, as well as forest-owners, farmers and other landowners.
3 Collection of background information	– Local actors prioritized improvement in water quality and return of migratory fish. Other environmental targets, such as climate change mitigation, were seen as more distant issues; while they were not opposed, they were considered important only if tangible results and compatibility with water quality related targets could be ensured. These results are elaborated more in Sarkki et al. (2024). – Based on a land use analysis of the area, the most important land uses in need of a change were forestry-drained peatlands and forests on mineral soil due to their large areal extent (Fig. 2). – Agricultural areas and peat extraction sites had smaller areal extents but were also important due to the large greenhouse gas emissions and exports of nutrients and suspended solids. – The exploratory analysis of water quality and fish stock development highlighted the past deterioration of situation but a slow and gradual improvement in the 21st century.
4 Piloting land use and restoration measures	– Local actors suggested multiple locations which export large amounts of nutrients and suspended solids to the watercourses. – The most relevant locations were checked with fieldwork. Five pilot sites were selected for planning in co-operation with landowners. – The sites were concentrated in the Nuorittajoki tributary due to its mediocre water quality based on local observations and official statistics (Finnish Environment Institute, 2024). – In each pilot site, wetland buffers or overland flow fields were planned and the implementation process including competitive tendering was started.
5 Visioning desirable futures and listing of development needs	– In the future visions, improvement of water quality and return of migratory fish were overarching objectives, followed by improved possibilities for recreational activities (fishing, paddling, nature-based tourism), active culture, well-being and new livelihood opportunities, catchment collaboration and co-ordination, and e.g., appreciation of mires as key ecosystems and cultural landscapes. – Development needs echoed the key visions and were related particularly to reducing exports of nutrients and suspended solids particularly from peat extraction and forestry, changes in society, financial compensations, policy instruments, changed attitudes, collaboration structures for catchment governance, increased collaboration with key actors (including landowners), and knowledge dissemination. – It became evident late at this step that simple technical land use solutions are not sufficient for governing and managing the change in the catchment, but larger changes in governance and society are needed. The results are elaborated more in Sarkki et al. (2024).
6 Assessing the impacts of potential land use measures	– According to modeling results, the detrimental environmental impacts of forestry on climate, waters and biodiversity can be reduced with forest protection, continuous-cover forestry, and wetland buffers. – Other water protection measures (buffer zones in mineral soil forests, peak runoff control dams, sedimentation ponds) are less efficient as are extended rotation periods in forestry (Nieminen et al., 2024). – Carbon emissions can also be significantly reduced by rewetting agricultural peatlands or managing peat soils by means of paludiculture, and partly also by their afforestation for which there are good possibilities in the catchment. Other agricultural measures have smaller environmental benefits. – Peatland restoration is particularly beneficial for biodiversity and reducing exports of nutrients and suspended solids while not necessarily for climate in the short-term (Kareksela et al. 2021). – For the after-use of peat extraction sites, the environmentally wisest options are restoration by rewetting and afforestation in drier areas (Räsänen et al. 2023, Aro et al. 2023). – Stakeholders emphasized particularly measures that have clearly observed or measured impact and for which landowners can get fair financial compensations. – Of the measures and potential sites, peat extraction sites and their after-use were considered important by stakeholders. – Continuous-cover forestry was partly favored but stakeholders considered uncertain whether it functions in the northern slow-growing and largely even-aged peatland forests. Its economic impact on forest-owners also raised concern due to the uncertainties in the calculations and a lack of scientific data. – Stakeholders also had hesitancy against rewetting and paludiculture of agricultural peatlands due to a lack of experience and uncertain economic impacts. – Stakeholders considered peatland restoration and forest protection good options if there were financial compensations, but forest protection was opposed in case if silviculture provided satisfactory income to the landowners. – The results are elaborated in more detail in Räsänen et al. (2024a) while the analysis of forestry-induced exports of nutrients and suspended solids is presented in Nieminen et al. (2024).
7 Discussing the impact assessment results	– The key targets remained largely unchanged from the previous steps and were related to water quality, fish stocks, and recreational use, but also to biodiversity. – The problems related to mitigating climate change through forestry measures were

(continued on next page)

Table 2 (*continued*)

Step	Key results
	discussed, as were the threats related to the plans to establish mineral mines in the catchment. The differences in the global and local perspectives were emphasized. – Most viable land use measures were considered to be wetland buffers, peatland restoration, and rewetting of peat extraction sites. – Multifunctional and multiuse landscapes were regarded as important, related e.g., to prioritizing peatland restoration to sites with positive biodiversity impacts but low economic value for the forestry sector. – Continuous-cover forestry, paludiculture, and afforestation of agricultural peatlands and peat extraction sites were considered less viable but still important. – Key governance measures were considered to be catchment-scale governance and collaboration between actors, financial support mechanisms, laws and regulations, and long-term planning and implementation of measures. – Challenges were related to the problems in managing common goods in areas with a fragmented land tenure, contradictory interests in how to use and manage forests, contradictory support mechanisms, and changes in political landscapes.
8 Synthesizing the land use roadmap	– The final roadmap (Räsänen et al., 2024b) was entitled "Towards clean waters, sustainable land use, and flourishing Kiiminkijoki region" and divided into three main sections: introduction and vision for 2050, targets for 2035, and measures to achieve the targets and vision. – The final roadmap text was prepared by researchers but was discussed thoroughly with the stakeholders. The texts were revised based on these stakeholder discussions and written feedback given through questionnaires. – The vision was "Free-flowing Kiiminkijoki is known and appreciated for its clean waters and salmon, while humans, livelihoods, and nature are living in harmony in its catchment". – The targets were related to water quality and fish, climate, nature and biodiversity, catchment governance, active local participation, recreational use, and sustainable natural resources economy. – The measures included both governance and land use measures, and contained catchment coordination, sub-basin-scale restoration plans, after use of peat extraction sites, management of point-source pollution, wetland buffers, peatland restoration, continuous-cover forestry, other forestry measures, river and stream restoration, rewetting and afforestation of agricultural peatlands, other agricultural measures, research and monitoring, communications and co-operation, and consideration of economic and other policy mechanisms (Fig. 5).
9 Establishing a catchment coordinator	– Catchment governance and the position for catchment coordinator was highlighted as the most important development target in the workshops for the Steps 5, 7, and 8. – It was emphasized that the task of establishing a catchment coordinator is not straightforward due to a lack of or weakness of support mechanisms and a lack of examples in Finland. The problems related to the structure of coordination were thoroughly discussed during multiple occasions. – A project grant application was developed in which the Finnish Forest Centre would take the responsibility for establishing the coordinator position and implementing the roadmap (Step 8), with a plan to pass the coordinator position to Kiiminkijoki River Association after the project.

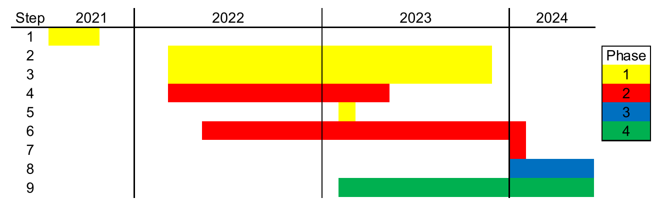

Fig. 3. The duration of the steps and phases in the Kiiminkijoki river catchment case study. The steps are described in Tables 1 and 2 and the phases in Section 2.1 and Table 1.

contradictions with other goals, as exemplified in an interview with an actor from an interest organization for farmers and forest owners:

> "In unclear situations, I would say that we should emphasize water protection. If the sludge ends up in the river, we cannot remove it, but the carbon sink we can compensate somewhere else."

The lack of emphasis for climate was evident also in the interviews with the environmental civil society actors, who were more concerned about direct threats to the water system by various industrial projects including new waste treatment plants, mining projects and groundwater extraction plans. Therefore, for reaching tangible results and broad co-operation, together with the stakeholders, we steered the focus towards water quality while climate change mitigation remained as one of the secondary objectives (a longer list of objectives is given in Table 2 and Sarkki et al. (2024)).

Results of the Phase 1 were complemented in the Step 5, in which the catchment vision and development needs were co-produced together with stakeholders in a participatory workshop (Table 2). The workshop further elucidated what kind of land use measures should be examined in the impact assessment and by which criteria (Step 6). Most critically, however, the workshop and work before that reinforced the perception that to make true changes in the catchment, implementation of land use measures does not suffice; instead, larger changes in actor collaboration and wider society are required. The need for coordination was expressed in an interview by an administrative official:

> "In this catchment area, there have been discussions about kind of a "water system janitor", or catchment level coordinator, so that there would be a comprehensive view and a practice by which drainage or water management would not be planned in isolation, but everything at once. (…) That also livelihoods opportunities and other objectives could be fitted together in this region. And in general, the resources that are after all quite scarce in water system management, could be directed where they are really needed or where we can reach better outcomes. That requires a comprehensive view."

4.2. Validation of knowledge production

The Phase 2 (Validation of knowledge production) consisted of the Steps 4, 6, and 7 (Table 2). Simultaneously with the Phase 1, land use and restoration measure planning and implementation were piloted in five areas considered critical by the local stakeholders (Step 4). The validation in this step was a two-way process. The local actors suggested potential locations for restoration measures (Fig. 4) that were checked by the project actors and communicated back to the stakeholders utilizing official water quality statistics, land use maps, and nutrient export simulations. The process was crucial in aiding to build a common ground for the necessary restoration measures and exemplified the measures that can be conducted in the catchment to the stakeholders.

Secondly, in the impact assessment and discussion on its results (Steps 6–7), the validation of knowledge and its production was a two-way process between the stakeholders and the project actors. Most of the impact assessment was conducted during 2023 but the work started already during 2022 through interviews. The impact assessment per se can be considered belonging to the Phase 1 (Making sense together) but it is included in the Phase 2 due to its two-way nature.

On the one hand, the stakeholders had an opportunity to contribute to what should be included in the impact assessment but only to a limited extent; with finite time and resources for scientific research, the impacts of every proposed land use or other measure could not be monitored or modeled. Instead, choices needed to be made what can be assessed. In our case, this meant focusing on simulation of forestry measures with the Monsu forest planning software (Pukkala, 2011) and GIS calculations for the rewetting and afforestation potential of agricultural peatlands utilizing soil type data and topography-based soil wetness (depth-to-water) index (Murphy et al., 2007). All the other impact assessments were based on literature reviews, and no empirical data were collected. However, the stakeholders' view was that empirical research should be conducted for certain measures. For instance, some forest experts expressed concerns regarding the effectiveness of the planned land use measures in a large catchment area with widespread drainage. A situation where the measures could have only negligible impacts on water quality or carbon sequestration but would at the same time cause significant economic harm for forestry was considered highly undesirable. For this reason, monitoring and assessing the impacts of the proposed land use measures was considered important by the interviewed forest experts.

On the other hand, scientifically produced knowledge can change local perceptions to specific measures, but only to a limited extent. For instance, it became evident in the forest simulations, that widely used water protection measures, such as buffer zones in mineral soil forests, sedimentation ponds, and peak runoff control dams have very little impact on exports of nutrients in the scale of a large catchment (Nieminen et al., 2024). This piece of knowledge was agreed by the stakeholders and such measures were not included in the final roadmap (Step 8). As an opposite example, stakeholders did not consider paludiculture or continuous cover forestry as prioritizable measures and showed hesitancy against their viability notwithstanding the scientific knowledge pointing to their environmental benefits. Continuous growth forestry was seen by many forest practitioners as generally unsuitable in Northern Ostrobothnia due to the climate conditions and ecosystem characteristics:

> "Continuous growth forestry is good at selected areas. If there is existing conifer undergrowth and the land is adequately nutrient rich, then sure it works. (…) If we then do it in the wrong areas, it might be that there is no growth anymore. We only might get the kind of old school selective logging forests that were historically even punishable by imprisonment. Now, we are intentionally making that kind of forests, and if they are done in wrong areas then the trees do not grow."

Nevertheless, these measures were included in the final roadmap, but so that their applicability was to be evaluated on a case-by-case basis. Overall, the validation phase not only helped to build a common ground on knowledge and its production but also showed the impartiality of scientific and local vernacular knowledge.

4.3. Usable outputs

In our case, the usable output (Phase 3) was the land use roadmap (Fig. 5; Step 8; Räsänen et al., 2024b) and an impact assessment report (Räsänen et al., 2024a) that acted as background information to the roadmap. There were multiple aspects that made the roadmap readily usable: it was built on a common understanding of the problem and had a holistic social-ecological view of the catchment (Phase 1), it integrated diverse knowledge sources and was properly and transparently validated and co-produced (Phases 1 and 2). Moreover, its uptake was discussed in workshops and a separate project was developed for its implementation (Phase 4). In short, its usability was linked to the process in which it was built highlighting the processual nature of actionable knowledge. Furthermore, the roadmap built a meaningful compromise between the different objectives; it not only concentrated

Fig. 4. We used printed maps in our workshops and other events to facilitate discussion about the catchment and to conduct participatory mapping. The participants, e.g., suggested potential locations for the restoration measures and marked sites of local interest. One of the authors of the article is sitting at the table.

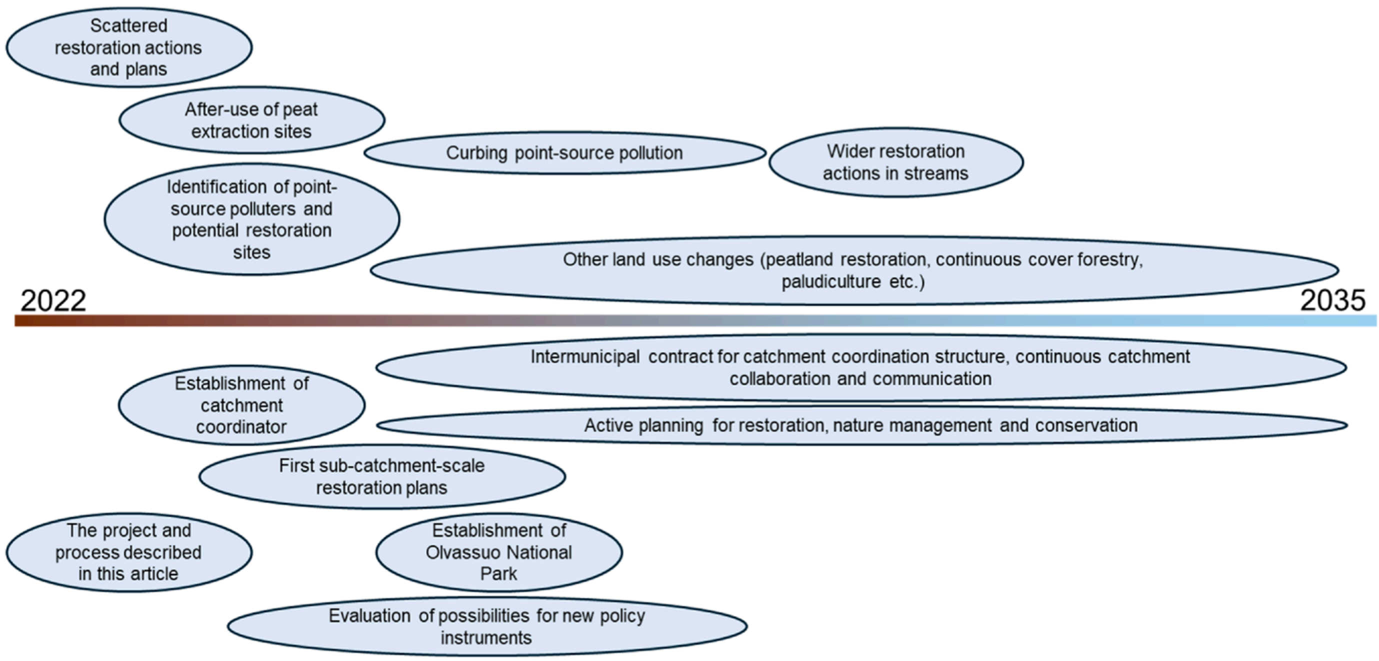

Fig. 5. Timeline of the different measures planned in the land use roadmap (Räsänen et al., 2024b). In the figure, land use measures are above the timeline while governance measures are below the timeline.

on improving water quality and local well-being, but it also included objectives related e.g., to climate, biodiversity, and economy. Despite these strengths of the roadmap, its usability can be properly examined only some years after its implementation. The processual aspects of usability and actionability also highlight the incompleteness of the roadmap: it can be developed further during its implementation and the written paper acts only as an initiator for action.

Stakeholders emphasized ensuring continuity of the process beyond the actual project outcomes. It was considered essential that the produced roadmap offered practical ways forward and included plans how the regional development is kept on track even after the initiators are no longer guiding the process. A couple of local civil society activists expressed their content with the project's objectives but also their wishes about concrete plans to continue the work:

> "R1: Overall, we are moving to a better direction, and it is surely great that we have these types of projects. And other large-scale projects have also been planned.
>
> R2: Yes, but there needs to be something tangible as well.
>
> R1: Exactly, so that we just don't get more papers to gather dust somewhere there.
>
> R2: And someone gets money for the planning and then it is…
>
> R1: Yes yes. Or someone does a PhD thesis about the topic and that's it. Instead, it should be transformed into an actual new practice."

Thus, in addition to the practical ideas of land use development, one of the key targets to make the produced knowledge actionable, is the establishment of the catchment coordinator.

4.4. Boundary spanning

The Phase 4 of actionable knowledge production (Boundary spanning) contained the establishment of the catchment coordinator position (Step 9). This phase happened concurrently with the other phases; even though the establishment was included as the most important measure in the land use roadmap, the process for establishing the coordinator started already during the Phase 1 because it was identified crucial already in the first interviews and workshops.

Many of the informants considered that the current land use practices are too fragmented and communication between the various stakeholders is lacking. Assessing the interconnected impacts of the various operations alongside the river is therefore difficult. A widely shared conception was that a properly resourced operator is needed so that the different land use measures can be coordinated among the wider network of actors. Currently, a few volunteer-based organizations such as the river association and the fishermen's association are working together with many of the regional stakeholders but cannot lead the coordination due to the lack of resources and a proper mandate for the task. Moreover, the existing official governmental organizations, such as the Centre for Economic Development, Transport and the Environment in the Northern Ostrobothnia, are reluctant to take the position as it is not part of their official duties.

The tasks planned for the catchment coordinator are partly related to bridging different knowledge sources and collecting and providing a holistic overview of the catchment. However, to make the knowledge actionable, the coordinator also needs to catalyze action across the administrative units and with the landowners; therefore, as highlighted in the workshop discussions, it should be the central node for knowledge and action within the catchment area. In the workshop that was used to finalize the land use roadmap, a participant stated the following about the potential role of the catchment coordinator:

> "Many restoration measures are good, but straight after them, there might be peaks in nutrient and suspended solids discharge to the water system. We must take this into account so that other improvements are not conducted simultaneously right when the discharge peak is incoming. So, let's coordinate!"

5. Discussion

We have illustrated how actionable knowledge has evolved during a transdisciplinary knowledge co-production process in the Kiiminkijoki river catchment. The endpoint of the process is a tangible and usable piece of information, i.e., a land use roadmap with targets and measures for catchment development. However, we see that more important than the usable output, has been the process of building the output and the associated process for collecting, analyzing and using the knowledge, and bringing various stakeholders around the same table. Hence, we highlight that the actionable knowledge in this case is not the output per se but the process of actionable knowledge production and use. This process does not even have a distinct endpoint as new actionable knowledge accumulates during the planning and implementation of the restoration and other measures. The forms of actionable knowledge and its production will need to change after the production of the usable output.

We acknowledge that understanding actionable knowledge as a process has both strengths and weaknesses (Table 3). Nonetheless, our argument on co-produced actionable knowledge as a process advances the literature on transdisciplinary research processes in three ways.

Firstly, current sustainability science and transdisciplinary literature commonly critique the linear model of moving from knowledge to action (e.g., Van Kerkhoff and Lebel, 2006). However, we observe and have shown that transdisciplinary projects may still have linear backbone in their approach where knowledge accumulates towards the end of the project and this does not exclude other forms of knowledge co-production processes taking place simultaneously.

Secondly, we emphasize a cyclical and iterative view on evolution of transdisciplinary projects (e.g. Hoffmann et al., 2019). We have illustrated that this takes place within the project's time span, but the transdisciplinary projects themselves are based on previous projects and produce novel starting points for subsequent research involving a larger number of actors. In addition, a cyclical and iterative research process contributes to the familiarity of involved stakeholders which enhances reciprocal relations and trust in general (cf. Luhmann, 1979; Putnam, 2000).

Thirdly, we contend with the view that transdisciplinary research based on knowledge co-production tries to make sense of the real-world complexity (Bergmann et al., 2021). This complexity is reflected in the idea of coevolution of knowledge and action (Chapman and Schott, 2020). To account for the coevolutionary complexity, a concept of meshwork deriving from Deleuze and Guattari (1987) and Ingold (2011) has been emphasized to capture "lines of becoming of researchers, stakeholders, and end users, which cross paths and get entangled into an encounter" (Klenk, 2018). The meshwork concept has been also connected to the messy interactions within a science-policy landscape that nevertheless explain whether and how knowledge moves to action (Sarkki et al., 2020). We propose that transdisciplinary projects can embrace the meshwork and manage the coevolution between knowledge and action by initiating boundary spanning activities (c.f. Bednarek et al., 2018).

In our case, the three approaches (cumulative, cyclical, coevolutionary) of actionable knowledge co-production process were all evident and the aspects interacted with each other. Even though we had a clear stepwise cumulative project structure which we followed, the cyclical aspect was visible in redirecting the focus and objectives of the process and in the fact that the steps of the process overlapped in time (Fig. 3). Furthermore, the coevolution of knowledge and action was evident when we paved way for the catchment coordinator that should be the central hub both for knowledge and action coordination.

The interaction between these three aspects of actionable knowledge building can be illustrated also in more general terms as done in the framework we propose (Fig. 6). Our framework diverges from the Hölscher et al. (2023) framework, which considers actionable knowledge either as knowledge-first or process-oriented, and focuses on systems perspective, agency and pathways of niche innovations in sustainability transitions. Instead of a such focus, generic phases in knowledge co-production processes are integral in our framework (Section 2.1). In the following, we discuss the three aspects of actionable knowledge building in more detail.

5.1. Actionable knowledge as a cumulative process

We suggest four general phases (Section 2.1, Fig. 6) in the process of co-producing actionable knowledge which proceed from co-defining the problem via roadmap to future position of the catchment coordinator. While knowledge can generate action at every phase and moment and while the points associated with different phases may be also relevant for other phases, we argue that accumulation of knowledge throughout the process increases its potential to generate action.

Firstly, in the co-production of knowledge phase (Phase 1), the integration of diverse systems of knowledge accumulates knowledge. In our case, social and natural scientific knowledge, diverse local knowledge, and administrative knowledge were being bumped into each other with the aim to integrate them towards knowledge that fits to the perspectives of diverse actors. Integration of knowledge systems has been considered as a key requirement for environmental science-policy interfaces to enable transformative change (Juhola et al., 2024). Integration of knowledge systems takes time but increases potential to generate action, as illustrated by wide acceptance of our roadmap. This was particularly facilitated by the fact that the same stakeholders were included throughout the process.

Secondly, in the validation phase (Phase 2), the knowledge system integration continues in a formalized way (e.g., through experimenting, commenting, evaluating) and the certainty of knowledge increases. Managing uncertainty has been regarded as a key issue to contribute to

Table 3
Strengths and weaknesses of actionable knowledge as a process.

Strengths
• Focus on the long-term process continuing after project's lifetime with the boundary spanning activities by the catchment coordinator.
• Builds trust between researchers and stakeholders that can improve collaboration possibilities in the future. Actionable knowledge can even be understood as a social process requiring attention to the trust between different actors (Stern et al. 2021).
• Emphasis on stakeholder ownership which is important for not focusing narrowly on specific pieces of knowledge but to the people and the process that generates action.
• Enables possibility to understand knowledge and action as coevolving processes in which knowledge is generated in all phases of the process instead of focusing on the knowledge which is co-created and presented in a particular format.
• The process brings together relevant stakeholders that might not necessarily work for a common goal without the process.
• Recognizes that actionable knowledge requires understanding of the social-ecological context in which the knowledge is produced. Practical solutions include considerations not only about the environmental issues and concrete management but also about the issues related to the relations between different stakeholders, as well as the contemporary and historical practices in the region.
Weaknesses
• May create confusion on how to catalyze and generate action if the outputs are not the only means of produced knowledge.
• Working together with societally relevant outputs is a good way to organize and motivate co-production activities among participants. Instead, a focus in process instead of outputs may distort the aims of the work if concrete outputs based on the work are not clear.
• Solutions that are essential but do not align with the interests of all relevant stakeholders may prove to be impossible to be implemented in practice. Besides, solutions for which available knowledge is contradictory may be difficult to implement if the co-operational nature of the process of defining the solutions is emphasized.
• Negotiation between stakeholders for different ways of knowing may dilute the ambitiousness of the process. This might lead to compromises in which there is not a sufficient focus on environmental questions to stop current development beyond planetary boundaries (e.g., Richardson et al. 2023). On the other hand, scientists may emphasize that producing scientific knowledge is not a democratic process and those with more scientific knowledge "know better" than the other stakeholders.

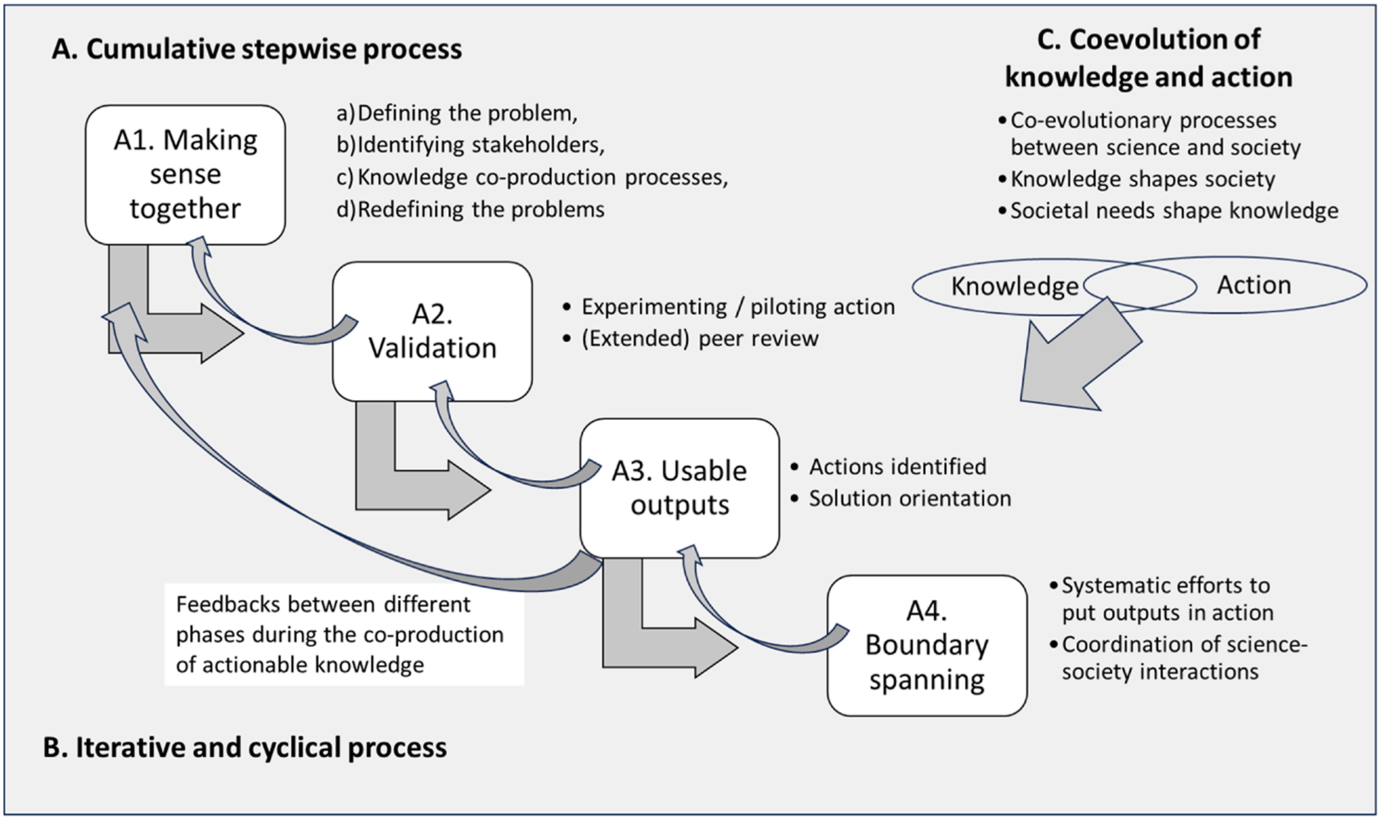

Fig. 6. Actionable knowledge as a cumulative, iterative and coevolutionary process. The cumulative stepwise process has four phases (A1-A4). The iterative features of the process are presented as feedback between the four phases of the cumulative process, and marked as B. The general coevolutionary process between action and knowledge is marked as C. The coevolutionary process is taking place all the time during the process, and it is challenging to manage due to complexity of knowledge and their users having different agendas, values, perspectives, and practices.

decision-making (Van der Sluijs, 2005; Wardekker et al., 2008). In our case, piloting land use solutions provided evidence on the applicability of the solutions, and transdisciplinary evaluation of our findings reduced the uncertainty of knowledge especially regarding its applicability. Yet, since the environmental impact assessment was based on modeling instead of empirical research, the uncertainties of the impacts remain. Overcoming and systematic dealing with uncertainties would increase acceptability for alternative land use and governance solutions. In our case, the uncertainties in knowledge led to compromises in which the final roadmap included tasks related to further examination of the case-specific applicability of the measures.

Thirdly, in the usable outputs phase (Phase 3), the mess of diverse bodies of knowledge and perspectives is reduced and clarified towards operational solution-oriented recommendations. The clarity of knowledge accumulates, and the messages it conveys become clearer. In our case, the creation of a short roadmap (Räsänen et al., 2024b) illustrates a simplification of the pool of results into a concise output that is easily accessible also to actors outside science.

Fourthly, in the boundary spanning phase (Phase 4), the focus is placed on what activities and measures are needed to supplement the produced knowledge to generate action. In our case, the catchment coordinator is the boundary spanner. It uses the generated actionable knowledge as a background but also seeks to build networks and enhance collective commitment behind the roadmap to have a holistic picture on the catchment development. At the same time, the production of actionable knowledge continues.

In sum, the four phases include different types of accumulation of knowledge towards action. Two generic forms of accumulation can be identified: the number of actors exposed to the co-produced knowledge increase as do the number of contexts against which the knowledge is reflected. These both increase opportunities for action based on the co-produced knowledge.

5.2. Actionable knowledge as a cyclical and iterative process

The initial objective of the process was to develop a plan for carbon storage and sequestration in the land use sector. Yet, in the beginning of the process during the negotiations with the stakeholders, it was discovered that climate change mitigation did not evoke a strong resonance among the local stakeholders, but water quality in the river was perceived consensually important. This implies that there may be disparity between problem-framing by science, policy, and local stakeholders. Scientific knowledge that seeks to solve a different problem than that perceived by stakeholders is not actionable. Sarewitz (2004) argues that science can make environmental controversies worse if value disputes need to be articulated by policy actors before scientific contributions to solve those problems. However, scientific knowledge can also change the perceptions of the stakeholders and contribute to solving the problems at hand.

In our case, if we had continued with a strong climate change focus, our project would probably have retreated from local definitions of the actual problems. During the past decades, local stakeholders have observed and experienced the deterioration of water quality and its impacts on many traditional activities in the river. Forest sector, peat industry, and local to regional administration have been considered to disregard the local viewpoints and ignore their contribution to the ecological state of the river system. Therefore, focusing primarily on another rather distant and abstract goal of climate change mitigation would have also decreased trust between researchers and local stakeholders. According to Jann and Wegrich (2007), a policy cycle starts with agenda setting and problem recognition. Thus, without a shared problem, there cannot be shared problem solving, and collective action becomes impossible due to different views on the underlying problem. In sum, to bridge the knowledge–action gap, the problem that scientific knowledge is addressing needs to align with the societal agendas for action.

There is a recent and growing interest towards transdisciplinary approaches that integrate various disciplines with stakeholder engagement, citizen science, and holistic perspectives (Pohl, 2011, Lawrence et al., 2022). Furthermore, transdisciplinary learning can contribute to sustainability transformations and to address real-world problems (Barth et al., 2023). In our case, such learning was based on integration of natural and social sciences with co-production of knowledge with stakeholders through two different aspects: piloting of land use measures and assessment of their impacts. In choosing the sites for pilots, official statistics were integrated with the knowledge of local stakeholders. Pilots also showed that the process may produce concrete results that solve locally relevant problems, instead of being a mere scientific knowledge production exercise without a link to concrete real-world practice. Local relevance reduced the distancing aspect of scientific knowledge. Furthermore, the impact assessment of different land use management alternatives integrated scenario modeling and stakeholder participation. Stakeholders had an opportunity to propose how the assessment was conducted and were able to comment on its results. This helped to ensure that the knowledge in the roadmap was relevant for the stakeholders. Nevertheless, an extensive focus on local needs might lead to compromises e.g., where restoration is spatially allocated to areas where it has little environmental benefits and causes minimal direct economic losses. In sum, actionable knowledge may be perceived as a cyclical and iterative transdisciplinary learning process (Fig. 6) which integrates strengths from both natural and social sciences together with local knowledge.

5.3. Ways to manage coevolution between knowledge and action

We find that actionable knowledge continues also after the research project has ended. Often, co-production projects face the challenge of project-based temporal scope limiting their impact (Turnhout et al., 2020). In our case, we hope that the roadmap will evoke a wide interest. However, we consider that normal dissemination and exploitation measures to enhance the actionability of the roadmap are beneficial but not sufficient. Therefore, the role of the catchment coordinator is critical to take necessary steps to put the roadmap into practice.

The need for a catchment coordinator and its establishment was one of the key pieces of actionable knowledge that was identified already in the beginning of the process. The coordinator position resembles the ideas of the European Commission to arrange their biodiversity and climate related science-policy interfaces by establishing a "one stop shop" (e.g., Bertoldi et al., 2021; Viti et al., 2024). Such arrangement can coordinate the science-policy landscape and function as a single-entry point for policymakers to knowledge. Other envisaged functions include building relationships between actors from society, business, science, and policy to have a holistic view on catchment governance, sustainability challenges and potential solutions, and for acting concurrently at the local, subnational, and national policy levels. In sum, actionable knowledge as a process continues also after the research projects have ended. Establishing boundary spanning positions to further bridge knowledge and action is a promising way to catalyze action. Such efforts can be also viewed as attempts to manage coevolution of knowledge and action by "meshworking" (Klenk, 2018) that creates new nodes into a complex landscape of actors and knowledge and take the advantage from an emergent situation to integrate different perspectives, as well as learn from diversity and difference.

The forms of actionable knowledge need to change in the different phases of the process. Our work described the build-up of actionable knowledge mostly on scientific, administrative and civil society levels. While we reached a meaningful compromise for the measures within the catchment, the measures cannot be conducted without an inclusion of landowners, forest-owners, farmers, and the residents of the catchment. Furthermore, also actors that emphasize economic profits need to be taken on board even though they have not been interested in the catchment development in the first place. In other words, the will in the local civil society and administration does not suffice to make sustainability transformations; instead, larger changes in the society, including societal values, landowner willingness, and forms of governance are required (Räsänen et al., 2019).

6. Conclusion

We have examined how the knowledge–action gap can be bridged by actionable knowledge as a process. Previous literature has focused on outputs and processes to create actionable outputs. We have emphasized that actionable knowledge is a continuous process that does not start or end with a transdisciplinary project relying on co-production of knowledge. Furthermore, we have shown that actionable knowledge as a process has three key characteristics. Firstly, it is cumulative stepwise process where knowledge accumulates as it is contextualized around a specific problem. This accumulation enables a concrete solution orientation in the examined empirical setting. Secondly, the process of actionable knowledge is iterative. Transdisciplinary projects often include changes in the problem framing and various kinds of feedback loops that may lead to revision of the objectives and activities. Thirdly, actionable knowledge is a coevolutionary process between knowledge and action, including messy relationships and building new connections between actors, various pieces of knowledge and perspectives. In practice, this means that already the early steps in a project can spur action, for example by building trust between stakeholders. Moreover, after the project, boundary spanning activities, conducted for example by the catchment coordinator, can open windows of opportunity. In sum, these characteristics show that actionable knowledge as a process is simultaneously cumulative, iterative and coevolutionary. Unlike what is often considered in research, these forms of process are not mutually exclusive but can occur at the same time. This realization can help to plan, implement and innovate transdisciplinary projects to contribute to bridge the knowledge–action gap. Overall, our nine-step approach can be used to develop sustainability transformations in catchment management and governance while the actionable knowledge framework and collaborative autoethnography can be used to critically evaluate the approach implementation.

CRediT authorship contribution statement

Sakari Sarkkola: Writing – review & editing, Methodology, Investigation, Formal analysis. **Matti Välimäki:** Writing – review & editing, Investigation. **Maria Isolahti:** Writing – review & editing, Project administration, Investigation, Conceptualization. **Kaisa Yliperttula:** Writing – review & editing, Investigation, Formal analysis. **Hanna Kekkonen:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Hannu I Heikkinen:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Karoliina Kikuchi:** Writing – review & editing, Investigation, Formal analysis. **Ville Koukkari:** Writing – review & editing, Investigation. **Katri Kärkkäinen:** Writing – review & editing, Investigation. **Janne Miettinen:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Erkki Mäntymaa:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Mika Nieminen:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Riina Rahkila:** Writing – review & editing, Investigation. **Aleksi Räsänen:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Anna Ruohonen:** Writing – review & editing, Investigation, Formal analysis. **Simo Sarkki:** Writing – original draft, Visualization, Investigation, Conceptualization. **Olli Haanpää:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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