UiT
THE ARCTIC
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Faculty of Biosciences, Fisheries and Economics
The Norwegian College of Fishery Science

Towards a Framework to Guide and Facilitate Interdisciplinary Social-Ecological System Research in Practice

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Charlotte Teresa Weber

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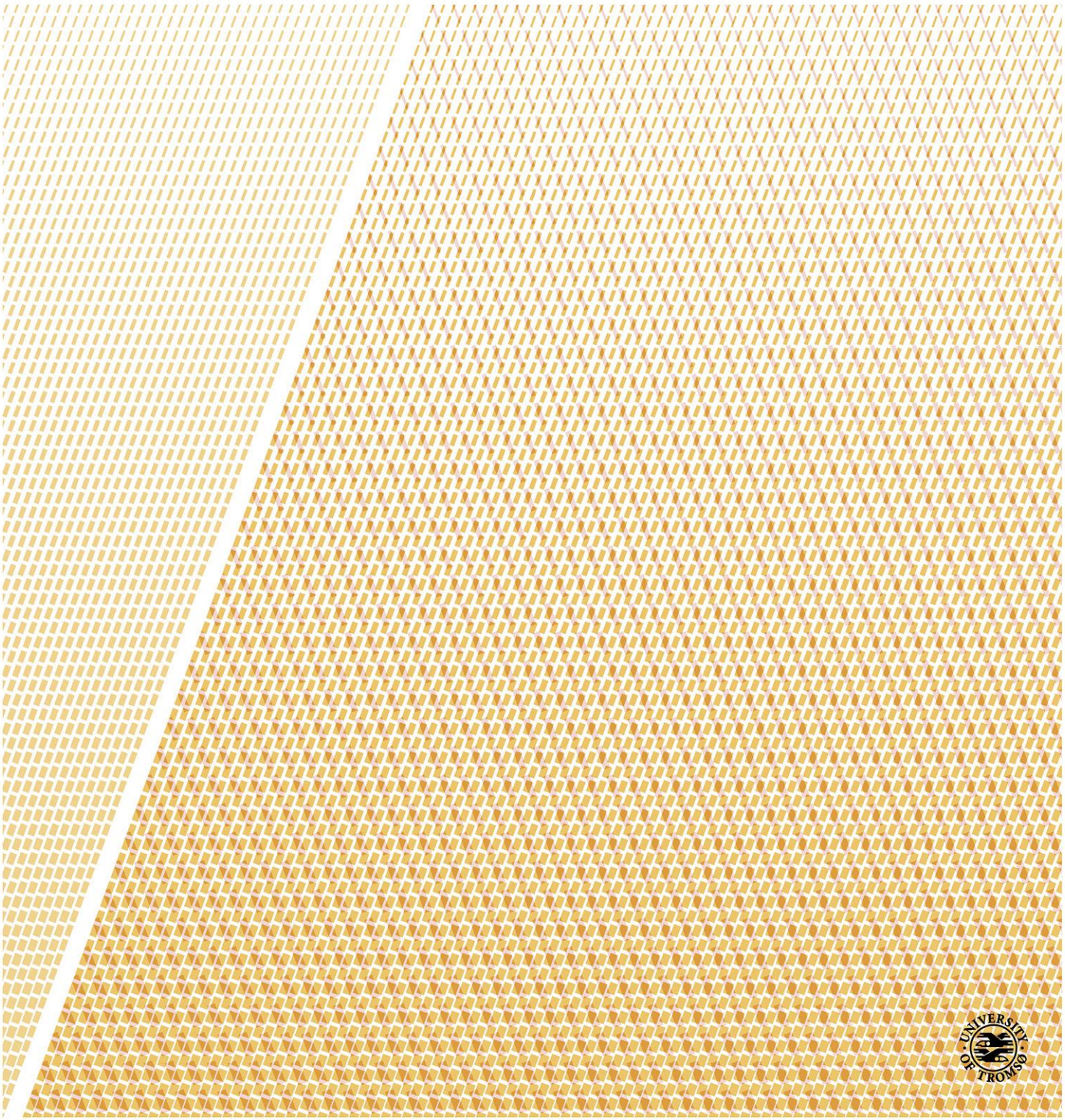

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A whole is more than
the sum of its parts.

ARISTOTLE

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Acknowledgments

This study is the result of a wonderful three-year journey, along which I have had the pleasure to meet some amazing souls and minds. This time was filled with many experiences that challenged me, brought me to my personal and intellectual limits, and made me learn and grow as a person and as a researcher. I was also presented with many fantastic opportunities, and for that I am very grateful. Many people have played important roles in and contributed to my life and my PhD process, and I would like to thank them here, in no particular order.

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Charlotte Teresa Weber

Glossary

Domain	A knowledge sphere; a body of scientific (sub-)disciplines that study a certain topic or system.
Framework	An analytical tool with several variations and contexts. It is used to make conceptual distinctions and organise ideas.[a]
Interdisciplinarity	Involvement of several unrelated academic disciplines in a way that forces them to cross subject boundaries in order to create new knowledge and theory and solve a common research goal.[b]
Model	A (coherent) representation of a system and/or the processes therein, which may consist of words, graphs, or equations.[c]
Multidisciplinarity	Involvement of several academic disciplines with multiple, disciplinary goals in parallel, often with the purpose of comparison, but does not cross subject boundaries or aim for any form of integration.[b]
Research Practice	A set of sayings or doings by individuals or groups for a particular purpose. Commonly each discipline has its own established research practices.[e]
Social-Ecological System	A coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner; a system that is defined on several spatial, temporal, and organisational scales, which may be hierarchically linked; a perpetually dynamic, complex system with continuous adaptation.[e]
Social-Ecological System Research	Research that clearly links the social and the ecological system, with the aim to understand relationships between social and ecological conditions, interactions, and outcomes. Always requires an inter- or transdisciplinary approach.[f]
Transdisciplinarity	Interdisciplinarity with additional involvement of non-academic participants that work towards a common goal in order to create new knowledge and theory through a collaborative and participatory approach.[b]

[a] Ravitch and Riggan 2012
[b] Tress et al. 2005a
[c] Hart and Reynolds 2008
[d] National Academy of Sciences 1992; Castán Broto et al. 2009
[e] Redman et al. 2004
[f] Ostrom 2009; Cumming 2014; Binder et al. 2013

Summary

Social-ecological systems (SES) consist of a social and an ecological system that are linked through a complex interplay of social and ecological processes. SES can be studied through SES research, which has become increasingly important because it is thought that it can potentially address and solve many societal challenges, such as climate change, resource scarcity, and habitat degradation. SES research investigates the relationships between social and ecological conditions, interactions, and outcomes, and requires an integrative, i.e. interdisciplinary or transdisciplinary approach, because one discipline alone cannot study the complex interactions within SES. This makes SES research particularly challenging and practical real-world barriers continue to hinder integration and progress in the field. Yet, the challenges and practical barriers for interdisciplinary SES research have hardly been explored, while practical guidance on how to conduct SES research is generally lacking.

As a first step to explore interdisciplinary SES research practices, a preliminary study is conducted with the aim to develop a framework that can guide researchers on how to conduct interdisciplinary SES research in practice. A preliminary framework is developed through a review and synthesis of various strands of literature and empirical experiences.

The framework provides ten design principles to guide the different phases of the interdisciplinary SES research process: the orientation phase—for problem identification, the preparation phase—for identifying relevant disciplines and team members, and the analysis and integration phase—for analysis, integration, and knowledge production. In addition, common practical challenges when implementing each of the design principles are outlined, while suggestions for practical coping strategies are provided to prevent or overcome these challenges. Three selected coping strategies proposed by the framework are demonstrated through practical examples, showing the application in practice of a particular methodology suitable to implement the respective coping strategy.

The preliminary framework could be applied by different users for various purposes, but its main intent is to make the SES research process easier on a practical level. The framework serves as a first step towards guiding and facilitating interdisciplinary SES research, from where an adjustment of the framework through co-creation with potential users or an expansion of the framework to guide transdisciplinary SES research, can be potential avenues for future research.

List of Papers

Paper 1:

Syed, S. & Weber, C.T. (2018). Using Machine Learning to Uncover Latent Research Topics in Fishery Models. *Reviews in Fisheries Science & Aquaculture*, 26(3), 319-336.
doi: 10.1080/23308249.2017.1416331.

Paper 2:

Weber, C.T. & Syed, S. Interdisciplinary Optimism? Sentiment Analysis of Twitter Data. Under review at *Royal Society Open Science*.

Paper 3:

Weber, C.T., Borit, M. & Aschan, M. An Interdisciplinary Insight into the Human Dimension in Fisheries Models. A Systematic Literature Review in a European Union Context. Accepted. Under second stage review at *Frontiers of Marine Science*.

Co-Author Contributions:

	Paper 1	**Paper 2**	**Paper 3**
Concepts and idea	CTW, SS	CTW	CTW, MB, MA
Literature study and references	CTW, SS	CTW	CTW, MB
Study design and methods	CTW, SS	CTW, SS	CTW, MB
Data gathering	SS	CTW, SS	CTW
Data analysis and interpretation	CTW, SS	CTW, SS	CTW, MB
Manuscript preparation and writing	CTW, SS	CTW, SS	CTW, MB
Inputs to the manuscript writing	CTW, SS	CTW, SS	CTW, MB, MA

Abbreviations for author names:
CTW – Charlotte Teresa Weber
MA – Michaela Aschan
MB – Melania Borit
SS – Shaheen Syed

Summary of the Papers

Paper 1. Using Machine Learning to Uncover Latent Research Topics in Fishery Models. Modelling has become the most commonly used method in fisheries science, with numerous types of models and approaches available. The large variety of models, and the overwhelming amount of scientific literature published yearly, can make it difficult to effectively access and use the output of fisheries modelling publications. In particular, the underlying topic of an article cannot always be detected using keyword searches. As a consequence, identifying the developments and trends within fisheries modelling research can be challenging and time-consuming. This paper utilises a machine-learning algorithm to uncover hidden topics and subtopics from peer-reviewed fisheries modelling publications and identifies temporal trends using 22,236 full-text articles extracted from 13 top-tier fishery journals from 1990 to 2016. Two modelling topics were discovered: estimation models (a topic that contains the idea of catch, effort, and abundance estimation) and stock assessment models (a topic on the assessment of the current state of a fishery and future projections of fish stock responses and management effects). The underlying modelling subtopics have shown a change in the research focus of modelling publications over the last 26 years.

Paper 2. Interdisciplinary Optimism? Sentiment Analysis of Twitter Data. Interdisciplinary research can face many challenges, from institutional and cultural, to practical ones, while it has also been reported as a "career risk" and even as "career suicide" for researchers pursuing such an education and approach. Yet, the propagation of the challenges and risks can easily lead to a feeling of anxiety and disempowerment in researchers, which we think is counterproductive to improving interdisciplinarity in practice. Therefore, in the search of 'bright spots', which are examples where people have had positive experiences with interdisciplinarity, this study assesses the perceptions of researchers on interdisciplinarity on the social media platform Twitter. The results of this study show researchers' many positive experiences and successes of interdisciplinarity, and as such document examples of bright spots. These bright spots can give reason for optimistic thinking, which can potentially have many benefits for researchers' well-being, creativity, and innovation, and may also inspire and empower researchers

to strive for and pursue interdisciplinarity in the future.

Paper 3. An Interdisciplinary Insight into the Human Dimension in Fisheries Models. Fisheries are complex adaptive social-ecological systems (SES) that consist of interlinked human and ecosystems. Thus far, they have mainly been studied by the natural sciences. However, the understanding and sustainable management of fisheries will require an expansion of the study of the human element in order to reflect the SES perspective. Models are currently the most common method used to provide management advice in fisheries science, and these, in particular, will have to expand to include the human dimension in their assessment of fisheries. The human dimension is an umbrella term for the complex web of human processes within a social-ecological system, and, as such, it is captured by disciplines from the social sciences and humanities. Consequently, capturing and synthesising the variety of disciplines involved in the human dimension, and integrating them into fisheries models, will require an interdisciplinary approach. This study, therefore, attempts to address the current shortcomings associated with the modelling of fisheries in the European Union and advises on how to include the human dimension and increase the interdisciplinarity of these models. We conclude that there is potential for the expansion of the human dimension in fisheries models. To reach this potential, consideration should be given to some aspects, e.g. early involvement in model development of all relevant disciplines, and the formulation of operationalisable theories and data from the human dimension. We provide recommendations for interdisciplinary model development, communication, and documentation in support of sustainable fisheries management.

1 Introduction

1.1 Motivation for this Study

Social-ecological systems (SES) are complex integrated systems in which humans are linked with nature through a complex interplay of social and ecological processes (Berkes 2011). SES consist of a social system and an ecological system that regularly interact in a dynamic and complex manner (Berkes and Folke 1998). The social system refers to the 'human system', which includes all human processes of economic, political, social, and cultural nature, as well as management and governance aspects. The ecological system refers to the biophysical system, including ecological processes, organisms, and communities that interact with each other and their environment. SES function in a two-way feedback loop, in which a change in one subsystem can impact the other, and vice versa (Berkes et al. 2006; Levin et al. 2012; Leenhardt et al. 2015).

At the core of the dynamic and complex interactions of SES lie many of today's complex problems and societal challenges. For example, climate change, biodiversity loss, resource scarcity, and habitat degradation are all complex problems that are driven by human activities and social dynamics (Binder et al. 2013; Fang et al. 2018). Yet, mankind depends on the natural world for life support, and it is, therefore, of importance to address and solve these complex problems and societal challenges for a sustainable future and human well-being (Redman et al. 2004; Ostrom 2009; Cumming 2014; Guimarães et al. 2018). Subsequently, there is a need for better understanding and the study of SES (McGinnis et al. 2012; Leslie et al. 2015).

SES can be studied through what is termed Social-Ecological System Research, or SES research in short (Cumming 2011; McGinnis et al. 2012). SES research has become increasingly important because it is thought that it can potentially address and solve many societal challenges, which are often both, ecological *and* social (Berkes and Folke 1998; Levin et al. 2012). SES research has a socio-ecological core (Cumming 2014), which means that it clearly links the social and ecological systems by investigating the relationships between social and ecological conditions, interactions, and outcomes (Ostrom 2009; Binder et al. 2013). Note that SES can also be studied in their separate parts, in which one or more disciplines investigate only one of the subsystems (either the social or the ecological system) or a single study object within a subsystem (e.g. the

study of fish stock recruitment in a fishery system). Such studies can take any form, from a mono-, to a multi-, inter-, or transdisciplinary approach (for definitions of these concepts, see the Glossary). Yet, studies lacking a clear link between the social and ecological system are considered not to be SES research.

SES research requires an integrative research approach (Redman et al. 2004; Stephenson et al. 2017; Dressel et al. 2018; Markus et al. 2018), because one discipline alone cannot study the complex interactions to address its social-ecological core (Collins et al. 2011; Cumming 2014; Guimarães et al. 2018). Integrative approaches, i.e. inter- and transdisciplinary, offer a synthesis from several disciplines and can incorporate the humanities, natural, economic, and social sciences, as well as non-academic stakeholders and knowledge bodies. Integrative approaches are inherently complex because both interdisciplinary and transdisciplinary research requires an integration of different knowledge bodies and disciplines. It is certainly not an easy task to integrate concepts, methodologies, procedures, terminologies, or data from different disciplines, especially when these are very disparate and have different ways of working, e.g. Biology and Anthropology (Apostel et al. 1972). Additionally, integrative research requires researchers to pay attention to many other aspects besides integration itself, for example, the choice of appropriate disciplines, the process by which they work together, and to ensure that individuals do not withdraw when conflicts arise (Pretty 2011). Additionally, interdisciplinary and transdisciplinary research faces many challenges, from structural and institutional challenges (Buanes and Jentoft 2009), to cultural (Chiu et al. 2013), and practical challenges (Lang et al. 2012; Pischke et al. 2017). As a result, a large body of literature has been developed in an attempt to help researchers in the study of SES.

Much of the SES literature has focused on the concepts and methodological approaches for the analysis of SES (Ravitch and Riggan 2012; Binder et al. 2013; Cumming 2014), while increasing numbers of SES case studies are being conducted within different domains (McGinnis et al. 2012; Hinkel et al. 2015; Partelow 2015; Liehr et al. 2017). Yet, despite the great interest of the research community in the study of SES, the interface between integrative approaches and SES research has hardly been explored (Cumming 2014). As such, the literature currently lacks guidance for integrative research dynamics in practice (Cumming 2014; Brown 2018). As a result, real-world barriers continue to hinder integration and challenge progress in the field (Redman et al. 2004).

A lack of integration is a major limitation for a research domain that intends to build "a strong interdisciplinary science of complex, multilevel systems[...]" (Ostrom 2007), because integration lies at the core of SES research and the field cannot progress nor advance without it. The widely dispersed literature on inter- and transdisciplinary research further hinders researchers from acquainting themselves with integrative concepts and applying them in practice (Lang et al. 2012).

Thus, the integration of different disciplines constitutes the weakest link in SES research (Cumming 2014), and there remains a general lack of practical recommendations to help researchers conducting inter- and transdisciplinary SES research. Hence, there is a need for practical approaches that can guide and facilitate the integration in SES research to lower the barriers for interdisciplinary and transdisciplinary SES research processes. Guiding principles could help researchers understand how to conduct integrative SES research in practice, i.e. how to *do* this type of research. For this purpose, it is thought that learning from the lessons of real-world interdisciplinary and transdisciplinary collaborations will identify and provide practical approaches for integrative SES research (Redman et al. 2004).

Investigations into *interdisciplinary* SES research practices and processes are needed as a first attempt towards guiding and facilitating SES research. Once guiding principles for an interdisciplinary SES research process have been identified and developed, they can then be expanded to a *transdisciplinary* approach. As such, guiding principles for *interdisciplinary* SES research can lay a foundation for any future guiding principles for the practice of *transdisciplinary* SES research.

1.2 Scope and Research Questions

As a first step to investigate and support interdisciplinary SES research practices, the objective of this study is to develop a preliminary framework that can guide researchers on how to conduct interdisciplinary SES research in practice. To do so, the preliminary framework provides guiding principles for an interdisciplinary SES research process. In addition, the framework aims to facilitate this research process by raising awareness of common challenges within the research process and by providing practical coping strategies to prevent and overcome these challenges. The main research question (MRQ) for this study was formulated as follows:

MRQ: *How can interdisciplinary SES research be guided and facilitated in practice?*

This main research question was divided into the following research questions (RQ):

RQ1: *What are the design principles for an interdisciplinary SES research process in practice?*

RQ2: *What are the practical challenges when complying with the design principles for interdisciplinary SES research in practice?*

RQ3: *What are the coping strategies to prevent or overcome the practical challenges of interdisciplinary SES research in practice?*

RQ4: *How to demonstrate selected coping strategies to prevent or overcome practical challenges of interdisciplinary SES research?*

RQ1 supports the MRQ by identifying how to *guide* interdisciplinary SES research in practice, whereas RQ2 and RQ3 support the MRQ by identifying what impedes and what *facilitates* interdisciplinary SES research in practice.

To ensure that the preliminary framework can support the *practical* challenges of interdisciplinary SES research, the framework is not only based on the theory of interdisciplinary and SES research, but also on the 'lessons learned' in empirical case studies with demonstrated successes and failures. The preliminary framework was developed via a literature review approach, as well as from the inclusion of the practical lessons-learned from two EU-funded projects—ClimeFish (2016) and SAF21 (2015) (see section 2.2.9 for more information on the projects).

To address RQ4, Papers 1–3 demonstrate three selected coping strategies of the preliminary framework in practice by applying an explicit methodology and providing concrete results. One of the papers (Paper 2) is applied to the academic context but without a domain-specific focus. Two of the papers (Paper 1 and Paper 3) are applied into the domain of fisheries research, in particular into the fisheries modelling domain, for the following reasons: (i) Fishery systems have been recognised as SES (Ostrom 2009), which makes fisheries a suitable research domain to demonstrate the coping strategies of the framework; (ii) modelling is the most commonly used method in fisheries science (Jarić et al. 2012) and amongst the most commonly used methods to study SES (Rissman and Gillon 2017); and (iii) this study is part of the project SAF21—Social Science Aspects of Fisheries for the 21^{st} Century (SAF21 2015)—which has the particular aim to improve the understanding of fisheries as SES.

1.3 Structure of the Study

The remainder of this study is structured as follows: Section 2 provides the scientific underpinnings of the study by addressing the concepts 'social-ecological systems' and 'interdisciplinarity', and a brief description of the EU projects ClimeFish and SAF21. Section 3 presents the methodology applied during the research. In Section 4, the results of the study are presented, followed by a discussion of the findings in Section 5 and conclusions in Section 6. The study ends with a self-assessment in Section 7, which provides an opportunity for critical evaluation and self-reflection regarding this study.

2 Background and Scientific Underpinnings of the Research

2.1 Social-Ecological Systems

2.1.1 Social-Ecological Systems Concept and Background

Social-ecological systems (SES) are complex integrated systems that consist of a social system and an ecological system, which interact in a dynamic and complex manner (Berkes and Folke 1998). The social system refers to the 'human system', which includes all human processes of an economic, political, social, and cultural nature, as well as management and governance aspects. The ecological system refers to the biophysical system, including ecological processes, organisms, and communities that interact with each other and their environment (Berkes 2011).

SES are understood as complex adaptive systems (Levin et al. 2012), and as such, the SES concept draws heavily on systems ecology and complexity theory (Cumming 2011). SES are **complex** due to the complex processes and behaviours that merge from the dynamic interaction between the social system and the ecosystem. Complexity is created through factors such as uncertainty, nonlinear feedback, cross-scale interactions, self-organisation, and emergence. SES are considered **adaptive** because they have the capacity to respond to their environments through self-organisation (Cumming 2011). As such, adaptation or adaptive capacity can be understood as "the improvement of fit between a system component or entire system and its environment. In evolutionary biology, adaptation is considered to be a passive process, in the sense that adaptation occurs through the action of selection on diversity. In social systems, a form of active adaptation, through decision making and proactive responses to environmental change, may be possible" (Cumming 2011).

Uncertainty is caused by the **non-linear relationship** between cause and effect in SES (Cumming 2011). Hence, nonlinearity is related to inherent uncertainty, as SES components interact in nonlinear ways that make responses and the effects of change difficult to predict (Levin et al. 2012).

Feedbacks, or feedback loops, describe a situation in which an effect influences its cause

(Cumming 2011). SES function in a two-way feedback loop, in which a change in one subsystem can impact the other, and vice versa (Berkes et al. 2006; Levin et al. 2012; Leenhardt et al. 2015). These feedbacks can be either positive, with an amplifying effect, or negative, with a dampening effect.

Self-organisation relies on the basic idea that open systems are able to reorganise themselves at critical points of instability. It is a process by which a system can modify its own internal structures and behaviours, often in response to external change (Cumming 2011). This principle is operationalised through feedback mechanisms within the system. However, the direction of the system under change is path dependent, as directions of change depend on, for example, the history of the system, and are therefore difficult to predict (Berkes et al. 2003).

Emergence, or emergent properties, result from critical relationships such as feedback and dependencies among components within SES, which cannot be understood by examining individual components (Knoot et al. 2010). Examples of emergent properties in SES include sustainability, or resilience, because these system properties arise from the interactions of a number of system components with one another and with their environment. These system components have the ability to process information and respond to internal and external change through action, adaptation, or learning (Cumming 2011).

Other important aspects in SES are **hierarchy** and **scale**. In this sense, SES are hierarchic, wherein every subsystem is nested within a larger subsystem (Berkes et al. 2003). Both the social system and ecosystem are nested. Hierarchical levels within a social system are, for example, governmental institutions on city level, provincial level, or national level. Whereas, Adriatic Sea, Mediterranean, North Atlantic, depicts a nested ecosystem with subsystems of different spatial scales (Cumming 2011). From such an understanding, scale and hierarchy can be defined as 'the spatial, temporal, quantitative, or analytical dimensions used to measure a phenomenon' (Berkes 2011). Studies of a particular SES will usually have to make a subjective choice regarding on which scale the analysis should take place (Cumming 2011). Phenomena within SES tend to have their own emergent properties and can occur at each level of these scales; the different levels may be coupled through feedback relationships (Berkes et al. 2003), with the levels being defined as 'the units of analysis located at different positions on a scale' (Berkes 2011). SES processes

commonly occur over a wide range of scales, which result in **cross-scale interactions**. This means that social and ecological processes can be coupled at each scale, smaller processes are embedded in larger ones, and larger-scale processes can also influence the smaller ones (Liu et al. 2007).

Modularity describes the degree to which the system's components may be separated and recombined, which is crucial for preventing harmful properties spreading throughout the system during the phase of change, and provides the building blocks with which to reorganise the system (Levin et al. 2012). Hence, modularity can be understood as the compartmentalisation of the system in space, in time, or in organisational structure. In this context, compartments are subsystems in which interactions between components are stronger than their interactions with system components outside the compartment (Cumming 2011).

Resilience is also an important concept for complex systems and SES. Resilience refers to the system's ability to continue functioning when exposed to either intrinsic or extrinsic disturbances. A system can thus be considered robust if it is resistant to change or able to reorganise after change (Levin et al. 2012). Many different definitions of resilience have been discussed but generally, resilience tries to capture the idea about the ability of a complex system to persist. However, resilience is not always necessarily a good characteristic or trait. Systems can be locked in a resilient state that is, from a human perspective, undesirable (Cumming 2011). Competing terms for resilience include robustness, sustainability, vulnerability, and fragility. However, as Cumming (2011, p.13) puts it: "Some scientists have tried to delineate minor differences between these different terms. In my opinion, such differences are more reflective of differences in the ways that different research groupings have approached the same problem than of fundamental differences in the nature of the problem being addressed".

2.1.2 Defining Social-Ecological Systems

The social-ecological systems concept is based on the understanding that humans are an integral part of all ecosystems, thus acknowledging the interconnectedness of humans and the environment. The term itself—'Social-Ecological System'—is meant to emphasise the co-equal interaction of the forces operating within the two systems (Redman et al. 2004). Based on Redman et al. 2004,

SES can be described though a four-pronged definition as follows:

- A coherent system of biophysical and social factors that regularly interact in a resilient and sustained manner;
- A system that is defined at several spatial, temporal, and organisational scales, which may be hierarchically linked;
- A set of critical resources (natural, socioeconomic, and cultural), of which the flow and use are regulated by a combination of ecological and social systems; and
- A perpetually dynamic, complex system with continuous adaptation.

In short, a social-ecological system can be understood as the interconnection of a human system and an ecosystem, which interact in a dynamic and complex manner over several scales.

2.1.3 Examples of the Social-Ecological Systems Concept Applied in Different Contexts

Generally, SES are investigated to understand certain drivers and interactions between system components, sudden events, and extensive, pervasive, and subtle change (Collins et al. 2011). As such, the SES concept can be applied to different contexts and case studies, which is why the conceptualisations of SES differ depending on the analytical focus and research question of the approach. Below, brief examples of SES case studies are provided, with the aim to facilitate a better understanding of the SES concept through real-world examples, and to demonstrate how conceptualisations, interactions, and system components differ, depending on the system under investigation and the purpose of the study. Additionally, figures of the conceptual SES under investigation are shown to allow for a visual representation of the interactions and feedbacks within the SES.

Land-use. Gardner et al. (2013) conducted an SES research study on land-use in Eastern Brazil Amazonia. The landscape provides significant benefits for human well-being through economic goods such as timber, and through ecosystem services such as climatic regulation. However, the area has also been under severe pressure through forest clearance, deforestation, and overexploitation, which poses a potential risk for irreversible damage to both the social and

ecological system. Therefore the study aimed to identify the problems within the system that should be addressed first and assessed the long-term implications of land-use alternatives in the landscape.

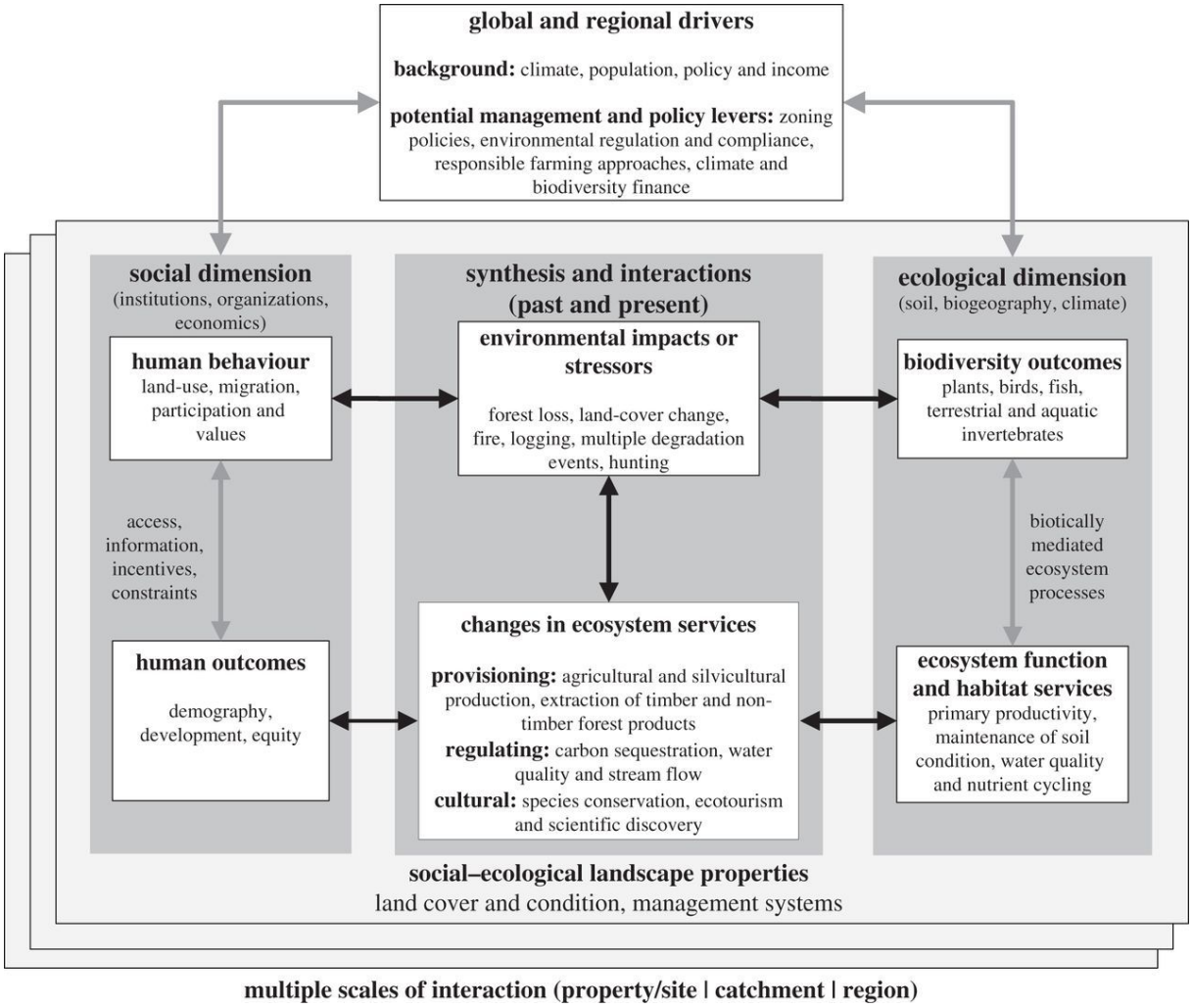

Figure 1 – Conceptual diagram of the social-ecological system of the landscape and its properties in Eastern Brazil Amazonia. The figure shows the interactions between system components, the social and ecological processes, the cause-effect relationships, feedbacks, and impacts. The social-ecological landscape properties, such as land cover and condition, are changes in landscape features that emerge, and that mediate relationships between social and ecological phenomena. System dynamics play out across multiple spatial scales. All the variables listed in the figure have been studied in this case study. Image from Gardner et al. (2013).

The SES approach was applied to identify the consequences of deforestation, forest clearance and degradation, and agricultural change on the system, to identify the factors within the system that can help explain the observed ecological condition, such as changes in biodiversity and soil chemicals, and to examine patterns of land use and farmers' well-being.

The conceptualisation of the case study SES as shown in Figure 1, highlights the drivers and interactions within the system: The dynamics of the ecological system are driven by the environmental impacts or stressors, which, in turn, are influenced or caused by human behaviour. Over time, the interactions of environmental impacts or stressors alter biodiversity outcomes and influence ecosystem functions and habitat services. Ultimately, this changes quantity and quality of ecosystem services that humans gain (human outcomes). Changes in human outcomes can affect human behaviour. For more info on this case study, see Gardner et al. (2013).

Agriculture & livestock production. In a study by Tenza et al. (2018), the social-ecological system under investigation is the oasis of Comondú in Mexico, representing a small-scale agro-system in a dryland. The oasis underwent a serious depopulation process that threatened its existence. Hence, the study aims to investigate the system's sustainability by identifying the drivers that have influenced the system and which drivers have led to a decline of this small-scale SES.

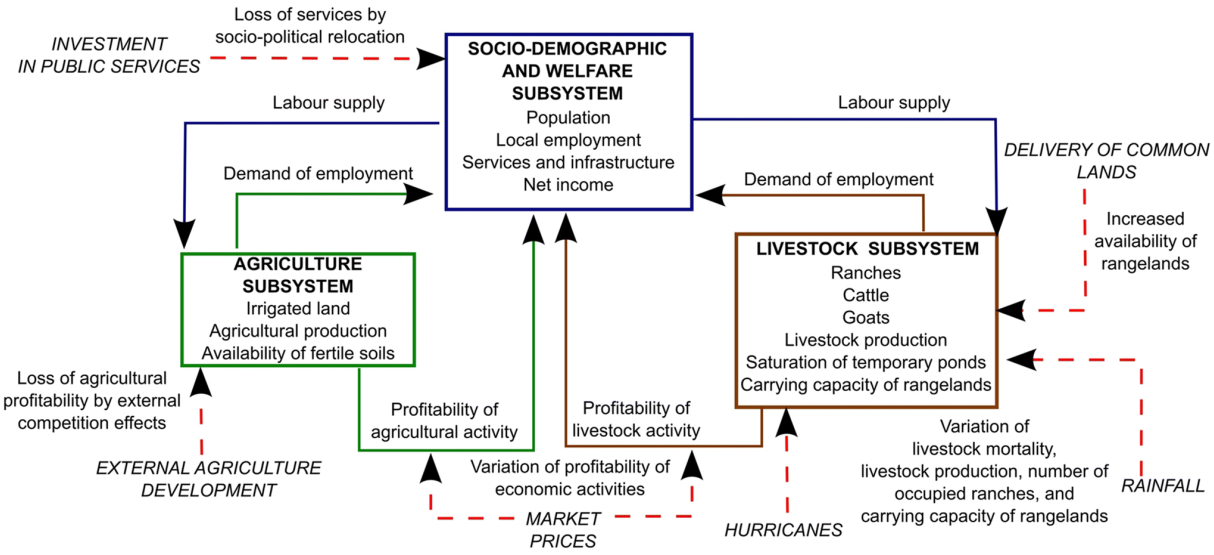

Figure 2 – Conceptual diagram of the social-ecological system of the oasis of Comondú. The external drivers are in italics and capital letters, and their effects on local dynamics are indicated with dashed lines. Image from Tenza et al. (2018).

The oasis of Comondú was conceptualised as an SES as shown in Figure 2. The SES is dominated by positive feedbacks between the socio-demographic and welfare system and the agriculture and livestock subsystem. The environmental limits to production activities in the agriculture

and livestock system act as negative feedback, which control the growth dynamics. In addition, the SES is exposed to external drivers, such as market prices, hurricanes, and rainfall. Each of the subsystems contains variables and interactions within, for example, the sociodemographic subsystem contains population deaths and births, and migration. Whereas the agricultural subsystem contains variables such as cost, profit, wages, competition and their interaction with each other. The livestock subsystem contains different types of livestock, such as cows and cattle, and variables such as births, deaths, predation, and sales. For more details, see Tenza et al. (2018).

Water Harvesting. In an example from Liehr et al. (2017), the process of rainwater and floodwater harvesting is evaluated from a system perspective and the SES concept is applied to a case study of a small-scale food production system in Central Northern Namibia.
This study took a problem-oriented research approach and was conducted with the aim to address water challenges in the area. Two technologies for rainwater and floodwater management had already been developed. However, it had been unclear how to adapt and embed these technologies in the area, so that they could provide a complementary source of water, food, and income. The SES concept was applied to embed the idea of rain and flood water management into a broader context. The conceptual representation of the SES is shown in Figure 3.

Farmers are the main actors of the social system that interact with the ecological system. Food consumers, traders, and constructors also interact with the ecological system through their demand for food, income, and labour. The key components of the ecological system are water storage in the soil and primary plant production, which depend on various biophysical factors. The two systems are interlinked through a feedback loop in which the demand for food drives water and land management, which, in turn, influences the ecological system and generates agricultural products. Consequences of management interferences with water, land, and soil include changes in natural structures and processes. Unintended side effects of management could be, for example, the harmful effects of pesticides on human health, or reduced ground water recharge due to increased water retention. For more details on this case study, see Liehr et al. (2017).

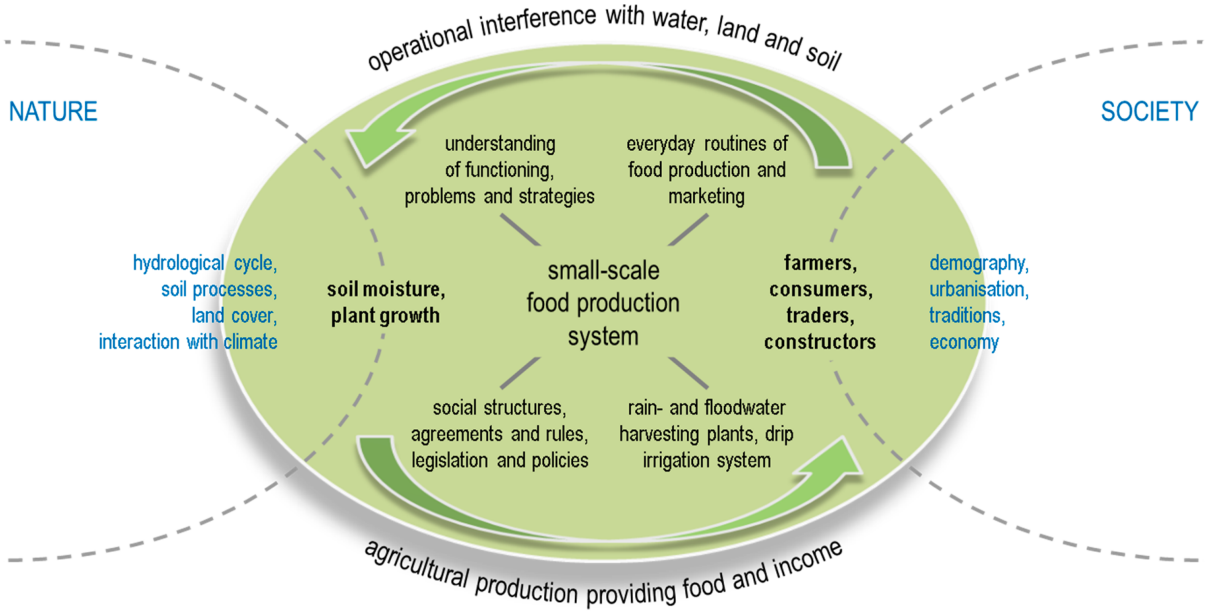

Figure 3 – Application of the concept of social-ecological systems (SES) to a case study of rainwater and floodwater harvesting as part of a small-scale food production system. Image from Liehr et al. (2017).

Fisheries. In a case study by Cenek and Franklin (2017), a Pacific salmon fishery in Alaska is investigated and conceptualised as an SES. The Alaska salmon fishery is a major social and economic driver in the area, which provides employment and subsistence, and also has a high cultural value for native Alaskans. The salmon is fished by various users, and active management is required to ensure the sustainability of the fishery.

The system was conceptualised as an SES to understand the interactions between the resource and the resource users, to identify the drivers that allow for enough salmon to escape, and to study the stability of the system. The SES approach allows for interaction between the different subsystems in the SES, and thus aims to capture the complexity of human behaviour and incorporate human uncertainty.

In the SES of the salmon fishery (see Figure 4), interaction occurs between the salmon (resource unit), fishermen (user), watersheds (resource system), and the fishery management (governance system). Interactions include, for example, the number of fish extracted, and when the governance system enforces regulations that will allow certain fishermen to fish, and others not. For more details, see Cenek and Franklin (2017).

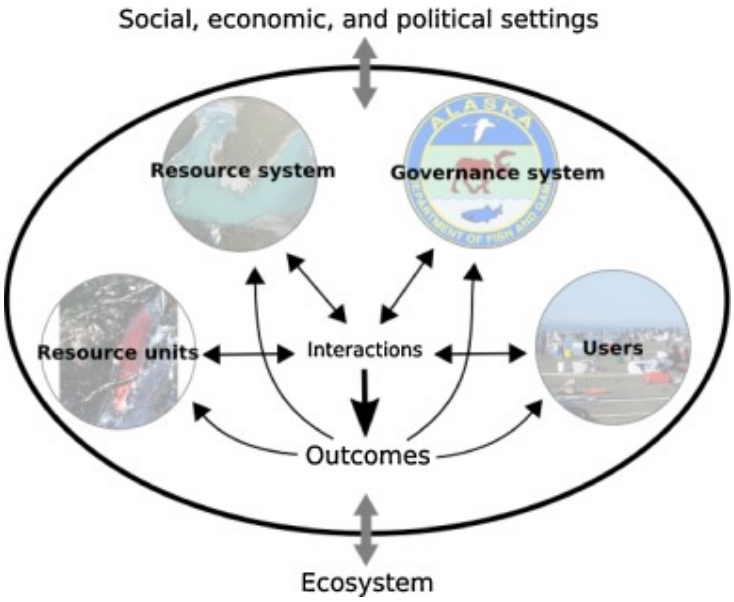

Figure 4 – Conceptual representation of the SES of the Alaskan salmon fishery. Image from Cenek and Franklin (2017).

2.2 Interdisciplinarity—Concept, Definition, and Practice

2.2.1 History of Disciplines

To understand the concept of interdisciplinarity, it is helpful to take a step back to the origin of disciplines. Since Aristotle, it was the philosopher's concern to divide, order, and classify the body of human knowledge, which was well connected to the need for teaching knowledge and for rational order, i.e. a controlled transition from one subject to the other. Hence, for the purpose of instruction, units of knowledge were generated and referred to as 'disciplines'—a teachable form of knowledge—derived from the Latin *discere*, meaning *learning* (Stichweh 1984).

Much later, around the 18th century, classifications of knowledge and encyclopaedic compilations were established in Europe because teaching areas of knowledge and sciences had become very diverse (Stichweh 1984). Disciplines were thought of as archives of knowledge deposits and unit divisions of knowledge (Stichweh 2001). Later in the 18th and 19th century, disciplines were described as production and communication systems, due to the early beginnings of specialisation. This was when scientists focused on small fields of science, and their specialised occupational roles were institutionalised by educational systems (Stichweh 2001). With specialisation came shared values and expertise among specialists, which formed the basis of specialist communities, and led to the emergence of scientific disciplines (synonymous with scientific community here). The emergence of scientific journals as the main form of communication demanded descriptions of scientific production processes, such as the method section, clear formulations of the hypotheses, and references to other scientists through citations (Stichweh 2001). Soon, research was understood as the 'search for novelties' and replaced the old notion of research as the preservation of knowledge. This transition led to the modern system of scientific disciplines, which is characterised by the establishment of disciplines in institutions (Stichweh 2001). It is also important to highlight that disciplines are dynamic and can expand and take up parts of other disciplines, with changing disciplinary boundaries. There is no hierarchy or centre, and all disciplines are considered equally important (Stichweh 2001).

2.2.2 What is a Discipline?

The classification and understanding of disciplines varied over time, depending on the institutionalisation of education and learning (Stichweh 2001). Also, the definition of a discipline varies among the different disciplines. However, the list below (based on Krishnan 2009) shows some of the more general criteria and characteristics that should be sufficient for the purpose of capturing the concept of a discipline:

- Particular object of research (can be shared with other disciplines at times)
- Body of accumulated specialist knowledge for the object of research, which is specific to that discipline and is not commonly shared with other disciplines
- Theories and concepts that can organise the specialist knowledge
- Specific terminology and technical language adjusted to the research object
- Specific research methods adjusted to the research requirements
- Must have an institutional manifestation, such as subjects taught at universities/colleges, respective academic departments, and professional associations

2.2.3 History and Developments of Interdisciplinarity

The modern term and phenomenon 'interdisciplinarity' did not emerge until the 20th century, but the basic ideas of unity of knowledge are much older. In ancient Greece, philosophers such as Plato had already talked about the undisciplined subject of philosophy as a 'unified science'. This initiated disputes about a lack of unity of science and the division of knowledge, which persisted throughout the centuries. Concerns about the overspecialisation and fragmentation of knowledge arose especially in the 16th through to the 19th century (Klein 1990a).

During the 20th century, discourse on interdisciplinary research increased, although the word *interdisciplinary* was first found in the literature of the social sciences and humanities in the mid-1920s (Frank 1988). Back then, it was the social sciences and general education that showed the most momentum for interdisciplinarity. Some colleges went through an era of general education reform that established programmes with the aim to move from a specialist to a generalist education. This was conducted through a curriculum that focused on a common set of

values, including interdisciplinary objectives, such as solving modern problems by assembling disciplinary resources (Klein 1990a). The establishment of the Social Science Research Council (SSRC) in New York in the United States, promoted the propelled integration across disciplines. A member of the SSRC addressed the Council's future research objectives as follows: "*There is a certain limitation in the fact that we are an assembly of several disciplines, and in our official statements again it is expressed that we shall attempt to foster research which brings in more than one discipline.* [...] *There would be no other body, unless we assume the function ourselves, charged with the duty of considering where the best chances were for coordinated or interdisciplinary work.*" (Frank 1988).

Later, during the post-war period of the 1930s and 40s, it became apparent that many of the problems of the time, such as war, propaganda, housing, social welfare, and crime, were too large to be handled by one discipline alone, which encouraged integrative thinking. This spirit led scholars, and governmental and private agencies to acknowledge the importance of interdisciplinarity and applied social sciences. Social science scholars from institutions, such as the University of Chicago and Yale, attempted to stress forms of interdisciplinary research and interdisciplinary fellowship programmes .

By the mid-1950s, interdisciplinarity was a common concept in the social sciences and discussions emerged on practical consideration, such as how-to-do-it manuals and interdisciplinary methods and problems (Frank 1988). However, interdisciplinarity remained an ambiguous term through the 1940s and 1950s and even into the 1960s. Both concepts, the idea of grant unity, as well as the more limited integration of existing disciplinary methods and theories, were frequently applied (Klein 1990a). Only in the 1970s, was one of the first typologies of definitions produced by the Organisation of Economic Cooperation and Development (OECD), to describe and distinguish the term *interdisciplinary* and others, such as *transdisciplinary*, *multidisciplinary*, and *cross-disciplinary* (Frank 1988; Klein 1990a). The book, entitled *Interdisciplinarity: Problems of Teaching and Research at Universities*, was released in 1972 (Apostel et al. 1972) and marked a major milestone in the history or interdisciplinarity.

The era of the 1960s and 1970s was a time of reform with elevated awareness for, and in strong support of, interdisciplinarity through major funding. This led to the establishment of many new educational programmes of which some still remain today. The founding of the programmes was supported by funding agencies such as the Carnegie Foundation in the Americas, and the

OECD and the United Nations Educational, Social, and Cultural Organisation (UNESCO) in Europe. The OECD then released a new definition of interdisciplinarity after a survey of the relationships between the university and community in their member countries. This was followed by the OECD's conclusion for an increased demand of interdisciplinarity outside of universities to address more 'practical' problems of the complex and technological 'real' world, in contrast to the university approach of producing new knowledge with the aim of achieving unity of science (Klein 1990a).

Since the 1970s, a huge amount of literature has been produced on interdisciplinarity and discussions on the topics have increased across disciplinary, professional, and general published scholarship. These discussions are becoming both broader and deeper, and have shifted, changed, and diffused their focus, from educational programmes and ideas of unity, to designing and managing interdisciplinary teams and research projects. In conclusion, the modern concept of interdisciplinarity has been shaped by historical ideas to obtain unity and synthesis, the emergence of interdisciplinary research and educational programmes, and by interdisciplinary movements over time.

2.2.4 Defining Interdisciplinarity

The term 'interdisciplinarity' is often seen as confusing because it encompasses such a broad field and has been varyingly described as complex, heterogenous, dynamical, and contextual (Schmidt 2008). For some, interdisciplinarity is a form of nostalgia for a lost wholeness, whereas others see it as a form of evolution in the sciences, thus causing uncertainty over its definition. Additionally, unfamiliarity with interdisciplinarity among scholars and an interdisciplinary discourse that is widely diffused among general, professional, academic, and other literature has made interdisciplinarity a divisive term (Klein 1990a).

Many definitions of interdisciplinarity exist in the literature, but all point in the same direction (Van Rijnsoever and Hessels 2011). For example, the OECD provides a relatively wide definition, which refers to interdisciplinarity as any interaction ranging from the 'simple communication of ideas to the mutual integration of organising concepts, methodology, procedures, terminology, data and organisation of research and education' (Apostel et al. 1972, p. 25), whereas Rhoten

and Pfirman (2007) understand interdisciplinarity as 'the integration or synthesis of two or more disparate disciplines, bodies of knowledge, or modes of thinking to produce a meaning, explanation, or product that is more extensive and powerful than its constituent parts'. Van Rijnsoever and Hessels (2011) focus on interdisciplinarity in relation to research collaboration and define it as 'the collaboration between scientists from different disciplines with the goal of producing new knowledge'. Interdisciplinary research (IDR) can therefore be thought of as a continuum of approaches rather than a uniform approach to research. However, in order to avoid ambiguity, the term *interdisciplinarity* is used and defined for the purpose of this study as follows:

Interdisciplinarity involves *'several unrelated academic disciplines in a way that forces them to cross subject boundaries to create new knowledge and theory and solve a common research goal'* (Tress et al. 2005a).

This means that the disciplines involved have contrasting research paradigms, e.g. qualitative vs. quantitative or analytical vs. interpretative approaches.

2.2.5 Drivers for Interdisciplinarity

Four primary motives and drivers for interdisciplinary research have been identified (National Academy of Sciences 2005):

- The inherent complexity of nature and society
- The drive to explore the interfaces of disciplines
- The need to solve societal problems
- The stimulus to produce revolutionary insights and generative technologies

One driver of interdisciplinary research is the inherent complexity of nature and society. For example, nature's complexity is apparent in some of the "grand challenge questions" of research like How did the universe originate? and What processes control climate? (National Academy of Sciences 2005). This driver also refers to the complexity of real-world problems that concern nature and society which are not easily solved and require crossing disciplinary boundaries, such as the challenges of sustainable resource use and eliminating world hunger (Repko 2008).

Interdisciplinarity is also driven by the desire to explore the problems and questions that lie at the interfaces of disciplines. Such investigations lead investigators beyond their own fields and can lead to discoveries or even the development of new fields. For example, Biochemistry is the result of such an interdisciplinary exploration, which has now departmental status at many universities (National Academy of Sciences 2005).

Societal problems, the third driver for interdisciplinarity, are certain kinds of problems that are of general public interest. These include problems such as food safety, access to education, terrorism, and immigration. These complex societal problems require expertise from multiple disciplines, and therefore, analysis and study of these problems requires an interdisciplinary approach (Repko 2008).

The last driver for interdisciplinarity is the desire to produce revolutionary insights and generative technologies. Revolutionary insights refer to those type of insights that transform how we learn, think, and produce new knowledge. Generative technologies are novel technologies that create applications of great value, and can also transform existing disciplines (Repko 2008). Examples of such generative technologies are the internet, GPS mapping, and the smartphone (National Academy of Sciences 2005).

2.2.6 Interdisciplinarity and the Disciplines

Interdisciplinary Critique of the Disciplines: The drivers of interdisciplinary research emphasise the value of interdisciplinary-based inquiries and the need to supplement disciplinary-based research. Yet, it also implies a critique of the disciplines and highlights weaknesses in the way disciplines operate. The interdisciplinary critique of the disciplines is discussed briefly, by touching on some of the weaknesses of disciplinary specialisation.

The first critique of the disciplines is that disciplinary specialisation hinders one to see the broader context, which can leave larger, more important issues, such as societal problems, unanswered (Repko 2008). Another critic argues that specialisation tends to produce tunnel vision and does not allow to capture the complexity of many of today's problems. However, many problems require an assessment from many different disciplinary perspectives to create a more comprehensive

understanding. This is because even the most highly educated and trained specialists may be unaware of all the social, ethical, and biological dimensions of a certain problem or action (Repko 2008). The lack of appreciation by the disciplines for other disciplinary perspectives is also seen as a weakness, while another critique argues that some problems are neglected because the fall between disciplinary boundaries. Interdisciplinarity argues that creative breakthroughs occur more often when different disciplinary perspectives are brought together, compared to disciplinary work (Repko 2008). Finally, disciplines are critiqued for being products of a bygone age. Some argue that disciplines were formed during an earlier historical period and that their silo approach to learning and problem solving is no longer capable of providing understanding for contemporary issues *by itself* (Repko 2008).

Disciplinarity vs Interdisciplinarity: The interdisciplinary critique of the disciplines is often perceived as a rejection of the disciplines by interdisciplinarity, and has resulted in some tensions between specialists and interdisciplinarians. However, interdisciplinarity is itself rooted in the disciplines, which are, as such, foundational to the interdisciplinary approach. Interdisciplinarity aims to offer an alternative way of knowing to disciplinary specialisation. Yet, the disciplines still provide the necessary grounding to a particular problem (Repko 2008). As such, interdisciplinarity does not intend to supersede the traditional disciplines but rather complement them (National Academy of Sciences 2005). Disciplines offer rigid, and conservative methodological rigour, exactness, and control for error. Interdisciplinarity can offer dynamic, flexible, liberal, integrative ways for bridging knowledge and finding unity, all that a single discipline might not be able to be or do (Weingart and Stehr 2000). It is, therefore, important to keep and nurture the disciplines as the ultimate reference point, while embracing interdisciplinarity (Krishnan 2009).
Much more has been discussed on the role of disciplines and their relation to interdisciplinarity (see, e.g., Krishnan 2009; or Jacobs 2017), but an in-depth discussion on this topic is outside the scope of this study.

2.2.7 Interdisciplinarity compared to Other Modes of Research

Besides interdisciplinarity, other modes of research exist. Without aiming to provide a detailed description and discussion of these modes of research, they are briefly illustrated below and

visualised in Figure 5. Generally, five different modes of research can be distinguished from each other: Disciplinary research, multidisciplinary research, participatory research, interdisciplinary research, and transdisciplinary research (Tress et al. 2005a). **Disciplinary**, also known as monodisciplinary research only has one specific goal within one of the currently recognised academic disciplines and recognises the artificial boundaries of that discipline. **Multidisciplinary** research involves several academic disciplines and has multiple, disciplinary goals in parallel, often with the purpose of comparison, but does not cross subject boundaries or aim for any form of integration. **Participatory** research involves academic researchers and non-academic participants aiming to solve a problem through knowledge exchange, but not with the aim of knowledge integration. **Interdisciplinary** approaches involve several unrelated academic disciplines in a way that forces them to cross subject boundaries to create new knowledge and theory and solve a common research goal. **Transdisciplinary** research combines an interdisciplinary with a participatory approach by integrating both participants from different academic disciplines and non-academic participants with a common goal to create new knowledge and theory through integration.

The main difference between these modes of research lies in the participants, academic and non-academic, and whether there is integration or not. Integration is only found in interdisciplinary and transdisciplinary research, which is why these are often referred to as 'integrative' approaches (Tress et al. 2005a).

2.2.8 Interdisciplinary Research in Practice

In practice, there is often a distinction between interdisciplinary research (IDR) and interdisciplinary education. Interdisciplinary education is often referred to as interdisciplinary studies (IDS) and can be practised in the form of interdisciplinary universities, undergraduate programmes, core curricula, and clustered courses, individual courses, independent studies, or as graduate and professional studies (Klein 1990a). However, the focus of this study is on IDR.

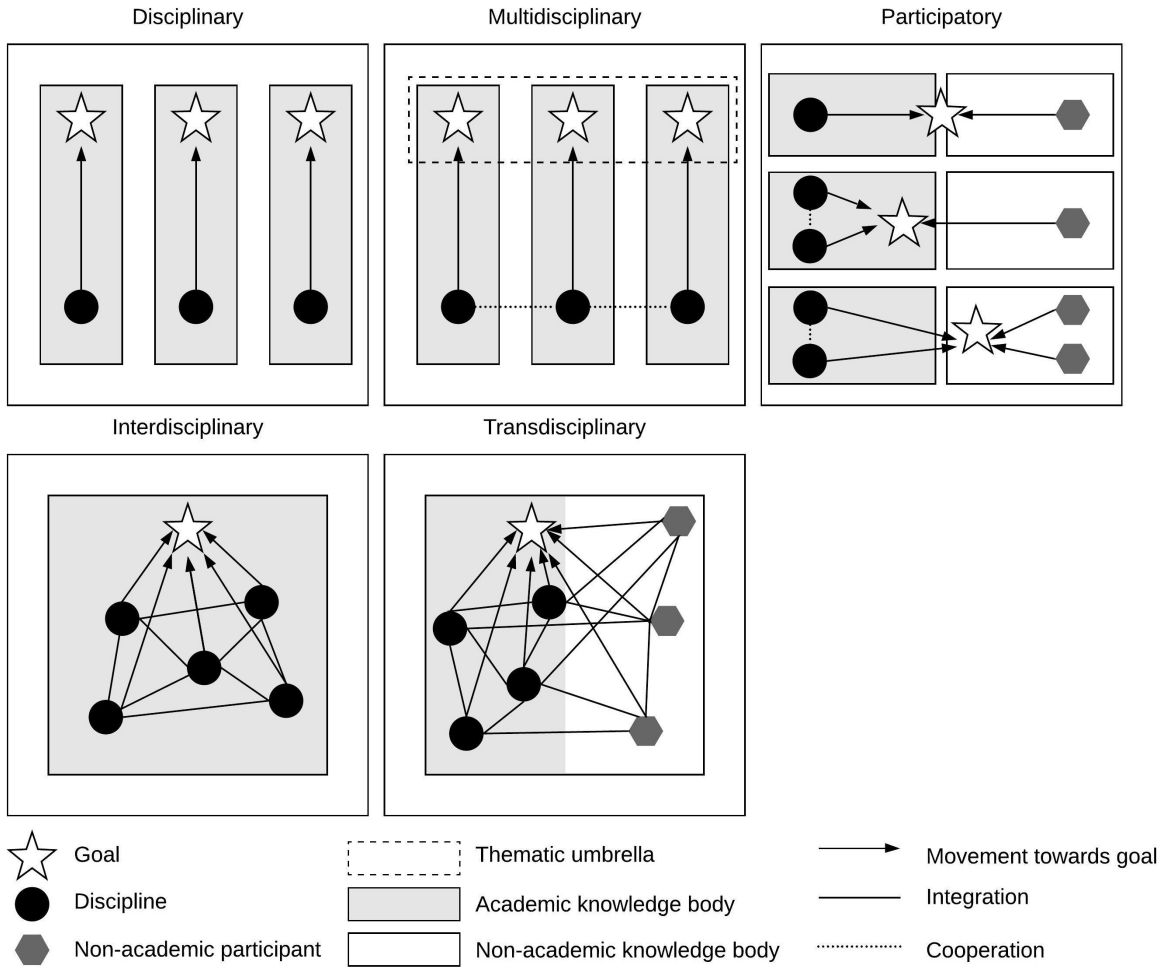

Figure 5 – Overview of research concepts. Image adapted from Tress et al. (2005b)[2].

Interdisciplinarity research practices exist in multiple forms, ranging from simple borrowing[1] to highly complex acts of knowledge integration and theoretical enrichment (Klein 1996). Interdisciplinarity in practice is, therefore, best understood as a variety of ways to cross, confront, and bridge prevailing single disciplines and approaches (Huutoniemi et al. 2010). Interdisciplinary research aspires to demonstrate the interfaces and frontiers of different disciplines to the researchers of those disciplines and to possibly even cross frontiers to develop new fields and disciplines. However, the motives for interdisciplinarity evolve from a variety of interests, and the form of practice will often depend on the interests that motivate the interdisciplinary path.

[2]Image adapted by permission from Springer Nature, *Clarifying Integrative Research Concepts in Landscape* Ecology by Tress, Tress and Fry, Copyright ©2018 by Copyright Clearance Center, Inc., 2005.

[1]The use of the tools, methods, concepts, and theories of one discipline in another is commonly known as 'borrowing' and 'cross-fertilisation' (Klein 1996). Sometimes a borrowing becomes so assimilated within a discipline that it is no longer perceived as foreign or borrowed. For example, electron microscopy originated within the physical discipline but has become a common tool within biological research (Weingart and Stehr 2000). See also the use of statistical methods by social scientists (Klein 1996).

Interdisciplinary research is also pluralistic in its modes of participation, in that it can be conducted in two different modes of participation: (1) in individual mode, in which a single investigator or researcher masters and integrates several fields; (2) in group mode, in which a group of investigators or researchers, wherein each has mastered one particular discipline, join together to work on a common problem through communication and collaboration (National Academy of Sciences 2005).

2.2.9 Examples of Interdisciplinary Projects: ClimeFish and SAF21

ClimeFish: The ClimeFish project is an EU-funded H2020 project (No 677039) financed under the societal challenges area of the Horizon 2020 funding programme of the EU, with a primary focus on research for innovation-related activities. The project addresses the societal challenge of food security under climate change by investigating the effects and challenges of climate change on fisheries and aquaculture. "The overall goal of ClimeFish is to help ensure that the increase in seafood production comes in areas and for species where there is a potential for sustainable growth, given the expected developments in climate, thus contributing to robust employment and sustainable development of rural and coastal communities."(ClimeFish 2016). To reach this goal, the ClimeFish project brings together a consortium of 21 institutes from 16 different countries, including non-academic stakeholders, which makes this not only an interdisciplinary project, but also a transdisciplinary one.

SAF21: The SAF21 project is an EU-funded H2020 Marie Skłodowska-Curie (MSC) European Training Network (ETN) (No 642080) with the primary focus on training a new generation of innovative PhD candidates. The project addresses the challenges of managing complex social-ecological systems by investigating fisheries systems from an interdisciplinary perspective. The overall goal of the project is to develop an integrated understanding of the fine mechanisms governing fishers' behaviour in relation to the regulative processes and the interplay and effects of such behaviour and processes on the ecological system. The aim is to use the knowledge from the project for better informed decision making and to develop innovative management strategies, to the benefit of decision makers, the fishing industry, and the environment. The project involves

10 PhD candidates that are based at seven different institutions and supported by an additional six partner organisations (SAF21 2015).

3 Methodology

The preliminary framework to guide and facilitate interdisciplinary SES research in practice was developed as a procedural framework, a framework that primarily provides sequences of steps or a set of planning guidelines (Cumming 2014). Procedural frameworks are often considered problem-oriented frameworks because they focus on applying theory, rather than developing or contributing to theory (Cumming 2014).

The framework development was based on an extensive literature review of interdisciplinary and SES research to answer each of the RQs (see Figure 6). An overview of the research process is briefly described here, and more details are provided below.

To address RQ1, design principles were developed and structured according to an ideal-typical interdisciplinary research process (see details below). For RQ2, the challenges to comply with the design principles and were identified, and for RQ3, the corresponding practical coping strategies, i.e. practical strategies that can be implemented to prevent or overcome practical challenges, were identified.

One of the main criticisms of many existing frameworks within the SES literature is the lack of comparison and incorporation of other existing frameworks (Cumming 2014). Therefore, a particular focus was put on the incorporation of existing frameworks from the literature during the development of the framework. As a final step, experiences and lessons-learned from two interdisciplinary EU projects ClimeFish (2016) and SAF21 (2015) were analysed and the coping strategies from within the projects were also included in the framework. The design principles, challenges, coping strategies, and existing frameworks were captured within the framework in a structured and coherent manner.

To address RQ4, three selected coping strategies of the framework were demonstrated through Papers 1–3 (Figure 6).

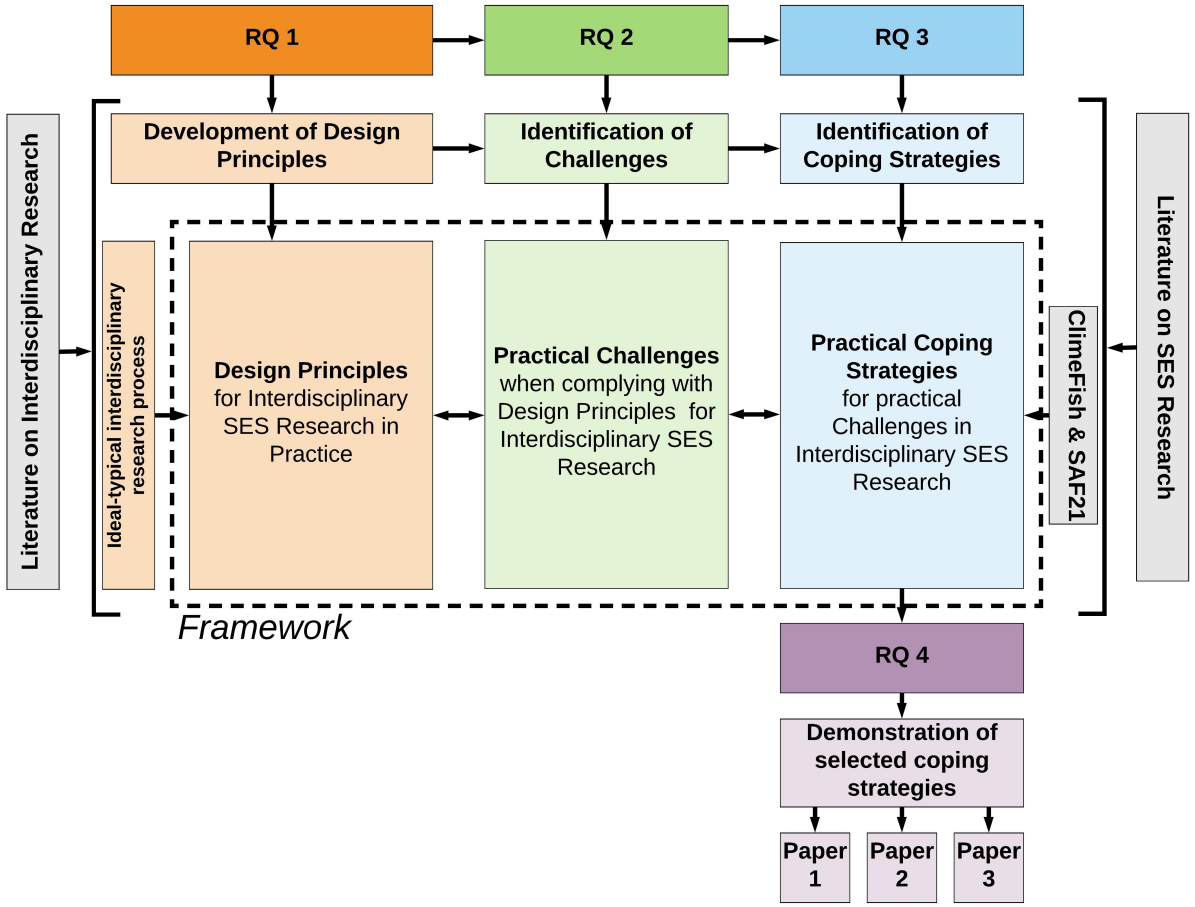

Figure 6 – Overview of the framework development in relation to the research questions (RQ). The literature on interdisciplinary research and on social-ecological system (SES) research was reviewed and synthesised to develop design principles for interdisciplinary SES research in practice, and to identify the practical challenges and coping strategies when complying with the design principles. Coping strategies identified within the EU projects ClimeFish and SAF21 were also added to the framework. Selected coping strategies were demonstrated through Papers 1–3.

Literature Review, Analysis and Synthesis. A literature review is an objective and thorough summary and analysis of relevant available research literature related to the topic being studied (Cronin et al. 2008). This methodology was chosen because literature reviews can be helpful to develop conceptual frameworks as well as to develop and update guidelines for practice (Cronin et al. 2008). The review process follows a number of steps (1–6, see also Figure 7).

(**1.**) Selection of a review topic. The topic selection was guided by the research questions, and therefore the two topics "interdisciplinary research in practice" and "SES research in practice" were chosen, which determined the main bodies of literature for the review: literature

on interdisciplinary research; literature on SES research in practice; and any literature that addressed the two topics together. The focus was put on research practices, which are the 'sayings' or 'doings' by individuals or groups when conducting research.

(**2.**) The analytical reading process progresses from the general to the particular. This progress involves skim reading through a body of literature and then picking out the specific papers that are relevant to the research questions. The process can be repeated several times (Hart 1998). During the analytical reading process, the comprehensiveness and relevance of the literature needs to be considered (Cronin et al. 2008). Following the analytical reading process, particular focus was put on literature relevant to the research questions, which narrowed down the relevant literature to publications with a focus on *practice*, whereby only literature relevant for the development of the framework was considered. Only peer-reviewed literature was considered for this purpose.

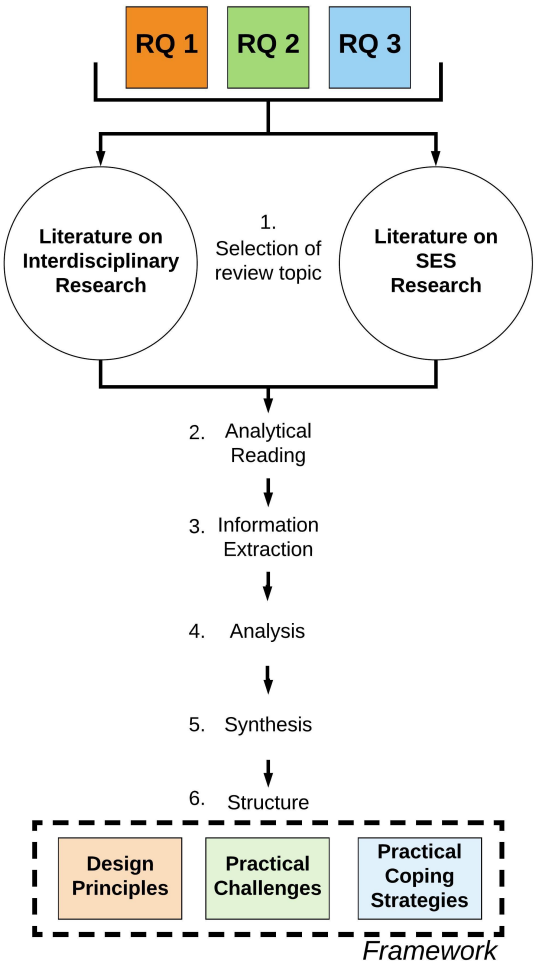

Figure 7 – Overview of the literature review process.

(**3.**) The relevant information was extracted from the literature.

(**4.**) During the analysis process, the researcher selects and differentiates between the information, to determine the organising principles between them and thereby identifying the main variables (Hart 1998). During the analysis, the extracted information from the interdisciplinary literature and the SES literature was examined and the main ideas and concepts were identified.

(**5.**) Synthesis is the process of integrating, combining, formulating, and reorganising the information derived from the analysis (Hart 1998). During the synthesis process, the analysed information from the two bodies of literature was integrated and combined to create new principles:

describing the process of interdisciplinary SES research in practice, thereby crossing the interface between interdisciplinary research literature and SES research literature.

(**6.**) The analysed and synthesised information was structured into the framework, based on the ideal-typical interdisciplinary research process.

This review method was used to develop the design principles for interdisciplinary SES research, to identify the practical challenges of this research process, and to identify the coping strategies to prevent and overcome the practical challenges of the interdisciplinary SES research process. These steps are explained in more detail below.

The **ideal-typical interdisciplinary research process** can be described through several steps (see Figure 8). These steps, based on Szostak (2013), are similar to what has been described by other authors (see e.g. Klein (1990b), Repko (2008), and Rutting et al. (2016)), and demonstrate what is generally considered important and commonly needed for an interdisciplinary research approach.

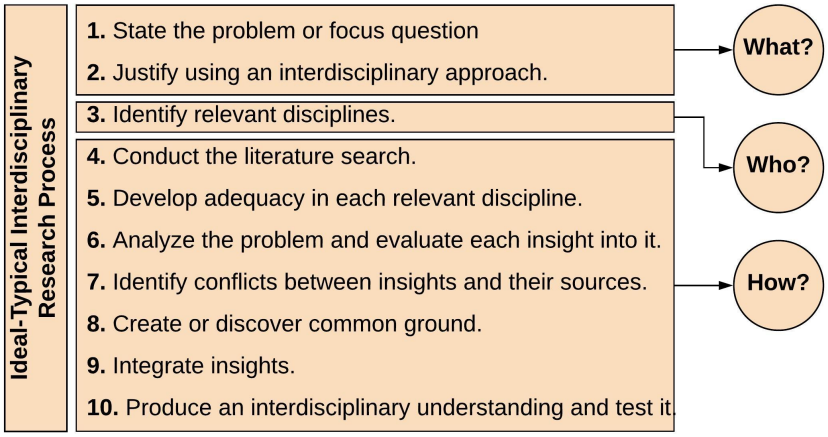

Figure 8 – The ideal typical interdisciplinary research process. The research steps are based on Szostak (2013), and were synthesised into three phases: '**What**' is the orientation phase for problem identification; '**Who**' is the preparation phase for identifying the disciplines and what scientists to include; '**How**' is the analysis and integration phase where new knowledge is produced.

The research steps were conceptualised into three phases: (1) '**What**' is the orientation phase for problem identification and framing; (2) '**Who**' is the preparation phase for identifying the necessary disciplines and building a collaborative team; and (3) '**How**' is referred to as the integration phase, but includes analysis, integration, and production of new knowledge and

insights through collaborative research. The research steps were conceptualised into three phases to generalise the research process.

Different strands of literature—drawing on the literature of SES research (e.g., Binder et al. 2013; Cumming 2014), and on the literature of interdisciplinary research (e.g., Pischke et al. 2017; Repko 2008; National Academy of Sciences 2005) in theory and practice—were reviewed and synthesised into comprehensive and practice-oriented **design principles** for interdisciplinary SES research. The design principles were structured into the three different phases of the interdisciplinary research process (Figure 8).

In the next step, exemplary **challenges** and corresponding **coping strategies** of the design principles, and **existing frameworks** were identified through a review of the literature and empirical case studies of interdisciplinary or SES research.

The design principles, challenges, coping strategies and existing frameworks were structured and presented within the framework, which is described in the Results section 4.1.

In addition to the review process, the **experiences from the two EU-funded H2020 projects** ClimeFish (2016) and SAF21 (2015) were analysed. The project proposal and the overall project execution (e.g. in terms of scientific workflow, project coordination and management procedures), and personal experiences (e.g. from meetings and teamwork experiences) were analysed to identify any applied coping strategies. Coping strategies were identified by assessing the project's proposals and procedures, which were applied for scientific processes and team management. Any identified coping strategies were added to the framework. First-hand insights into both of these projects and their internal procedures were available because I was a PhD Candidate in SAF21 and I am employed as a researcher for ClimeFish at the time of writing this study.

In a final step, three coping strategies and three corresponding methodologies were selected to demonstrate these strategies. The Papers 1–3 demonstrate these strategies and methodologies. The methodologies are explained in detail within the individual papers.

4 Results

4.1 Framework to Guide and Facilitate Interdisciplinary Social-Ecological System Research in Practice

Framework Condition: Before applying the framework, a condition needs to be fulfilled: the study for which this framework will be used needs to qualify as SES research (see Glossary or Introduction). Only when this condition is fulfilled can the application of the framework be useful to guide and facilitate the planning and conduction of the study.

The framework developed in this preliminary study describes the design principles (A1–3, B1–3, C1–4), challenges, and coping strategies for conducting interdisciplinary SES research in practice, which are explained in detail below, and summarised in Table 4.1 at the end of the section.

A: Orientation phase—What?

- **A1**: *State the problem or research question.*

The research problem needs to be clearly defined within the social-ecological system context and trigger a scientific research question. This design principle can be challenged through a lack of guidance on research priorities and by difficulties to identify research gaps within an SES domain (Cumming 2014). In addition, if issues are not perceived as problematic due to a lack of problem awareness and recognition, a common problem definition can further be challenged (Lang et al. 2012). To overcome these barriers, firstly, a pre-assessment or pilot study can be conducted to raise problem awareness while assessing the status quo, e.g. through an overview of past research trends or a gap analysis. Research priorities can be set by identifying pressing societal challenges within an SES that need to be addressed (Brown et al. 2015), e.g. based on the United Nation's Sustainable Development Goals (United Nations 2015). In addition, all team members should be involved in the framing of the problem and definition of the research question to find common ground (Morse et al. 2007). A clear problem definition can be facilitated by using the framework for interdisciplinary problem framing by Clark et al. (2017), who offer the following guiding principles and questions: Clarify goals (value task): what are we trying to accomplish? (2) Map trends (history task): what has happened? (3) Identify conditioning factors (explanation task):

why has it happened? (4) Make projections (futuring task): what is likely to happen in the future? and (5) Develop and evaluate alternatives (practical task): what are we going to do about it?

- **A2**: *Consideration of theoretical elements for the study of SES.*

SES are inherently complex and therefore studying them requires the consideration of theoretical frameworks that can guide the conceptualisation of SES and an effective analytical focus (Cumming 2014). Yet, not one theoretical framework can provide sufficient theory for all feasible situations (McGinnis et al. 2012). Consequently, there has been a growing body of scientific theory on SES (Cumming 2011, p. 7) and many different frameworks have been developed to structure SES research (Ostrom 2009; Binder et al. 2013; Cumming 2014). These frameworks differ significantly in their goals, applicability, and conceptualisation of the SES, which hinders comparison of the frameworks and the diversity of results. In addition, researchers tend to develop new frameworks without fully explaining what its new elements are and how it relates to existing frameworks (Cumming 2014). The high diversity of frameworks, lack of overview, and uncertainty about strengths and weaknesses of the available frameworks, make it challenging to choose an appropriate framework for a particular research question (Binder et al. 2013).
To overcome these challenges, Binder et al. (2013) provide guiding questions for the selection of an appropriate framework as well as a comprehensive review of established frameworks one could possibly draw from. Additional reviews on existing frameworks should also be considered, like the one provided by Cumming (2014). The quality of these theoretical frameworks can then be assessed through the seven criteria for theoretical frameworks (Cumming 2014), to highlight strengths and weaknesses, and to evaluate whether they are suitable for the interdisciplinary SES study in question. These seven criteria can be summarised as follows (based on Cumming (2014)):

1. Social-ecological core: frameworks need to clearly link the social and the ecological system and be strong in both the social and the natural sciences.
2. Empirical support and translation modes: frameworks should be supported by rigorous empirical studies and should include translation modes that allow empirical observation to be connected to theory and vice versa.

3. Mechanisms: frameworks should be able to provide insights into causality and should offer explanations for the observed complex behaviours in real-world SES.
4. Spatio-temporal dynamics: frameworks should deal with the spatial nature and spatial variation of SES, as well as the nature of change through time.
5. Disciplinary context: frameworks should relate to previous frameworks and strive for synthesis between previous work, while highlighting their weaknesses and strengths.
6. Interdisciplinarity and transdisciplinarity: Frameworks should offer connections between, and cope with, complementary perspectives and different disciplines.
7. Direction: Frameworks should offer direction for the study of SES to advance our theoretical understanding of them.

- **A3**: *Justify and promote benefits of using an interdisciplinary approach.*

Interdisciplinary SES research requires an interdisciplinary approach. However, not every research question allows for an interdisciplinary inquiry. Similarly, some theoretical frameworks for the study of SES do not support the integration of different disciplines. Another challenge for an interdisciplinary approach may also be a lack of support by the researchers and research community. Researchers with negative perceptions and attitudes may not want to engage in interdisciplinary studies, and thereby also de-motivate others from doing so, or create a fear of failure. These attitudes and fears can hinder the creativity and innovation potential in researchers, and, as such, impede the interdisciplinary research process (Schleier and Carver 1993; West et al. 2009b; Rego et al. 2012; Darbellay et al. 2017).

To overcome these challenges, firstly, the formulated research question must be able to justify the interdisciplinary approach. The following criteria can be used to identify and justify if and why the research question and study requires an interdisciplinary approach (National Academy of Sciences 2005): (1) The problem or question is complex; (2) Important insights or theories of the problem are offered by two or more disciplines; (3) No single discipline has been able to address the problem comprehensively or resolve it; and (4) The problem is an unresolved societal need or challenge.

The underlying SES-theory should also be selected with care, to ensure that it allows for an integration and linkage of different disciplines, as already highlighted above (see guiding questions by Binder et al. 2013; and quality criteria by Cumming 2014).

The perceptions and attitudes of researchers towards interdisciplinarity can be assessed before starting the interdisciplinary project. An assessment can identify if and why researchers feel negatively about interdiscplinarity. These negative perceptions can then be targeted and addressed, to increase positive perceptions and thereby researchers' support. To gain the support of researchers for an interdisciplinary approach, it is important to foster optimism, positive thinking, and create a stimulating environment that enables team positivity and creative thinking. Optimism, positive thinking, and awareness of the importance and benefits of interdisciplinarity can be fostered by highlighting 'bright spots' (Cvitanovic and Hobday 2018). Bright spots are those instances in which interdisciplinary science and researchers have been positive and successful, and the benefits of interdisciplinarity are clearly shown. When people feel optimistic about their research endeavour, it increases their creativity and innovation potential, and has a positive effect on team work (Scott and Hofmeyer 2007; West et al. 2009a; Rego et al. 2012; Tang and Werner 2017).

B: Preparation phase—Who?

- **B1**: *Identify and select relevant disciplines.*

Disciplines that can substantially contribute to the problem and research question with their theories and insights should be selected. A common challenge is to identify relevant disciplines, weigh up their necessary contribution, and develop an understanding of the different disciplinary perspectives on the research topic. Relevant disciplines can easily become underrepresented during the research process if they have not been identified correctly or vice versa, where too many unnecessary disciplines are participating (Repko 2008). It can be very tempting to rely on an already existing network of research collaborators, the "usual suspects", the people who have previously been involved in research projects and who are generally interested in an interdisciplinary SES approach. However, selection of participating disciplines should be based on predefined expertise and expert selection criteria, informed by the framing of the problem. In addition, SES research requires that both the social and ecological system are considered, which means that both the natural and the social sciences should be involved in the SES research process (Cumming 2014).

To identify relevant disciplines in a structured manner that justifies their participation, the

research question and SES theory can be 'mapped' with the potentially relevant disciplines (Repko 2008). This can be achieved through a research map, which explicitly states the purpose of the research, identifies what disciplines are potentially relevant to address that research, states the perspective of each discipline, and identifies assumptions of each discipline (Repko 2008, p.149). A competence matrix can be used to map the competences found in different disciplines to specific tasks within a project. This can help to identify overlap or lack of required disciplinary competences (ClimeFish 2016)[3].

- **B2**: *Identify and select relevant research team members.*

Members of interdisciplinary teams are often selected based on their disciplinary expertise. Yet, a common challenge when building an effective interdisciplinary research team can be to find personnel and team members with good interpersonal skills and who have shared goals (Halvorsen et al. 2016). A lack of interpersonal skills as well as conflicts in personality types among team members can strongly hinder interdisciplinary team work (Romero-Lankao et al. 2013; Pischke et al. 2017). Problems also occur when prejudices, reservations and resistances persist within disciplines when it comes to working with disciplines that are 'not your own' (Paterson et al. 2010).

One important aspect for any successful team is the selection of an interdisciplinary team leader. Leaders of interdisciplinary teams require a special skill set for them to be successful. They require high levels of intelligence, educational status, self-confidence, and sensitivity to the socio-emotional needs of the team members (Stokols et al. 2008), while they should also have a multi- or interdisciplinary expertise (Salazar and Lant 2018). Team leaders need to be assigned at the beginning of the project, so that they can delegate and help to get the team focused on preparation, maintaining cooperation, and providing a contact point for questions or problems during the project (Pischke et al. 2017). Team leaders should also encourage shared responsibility, individual and group accountability, flexibility, creativity, and patience among team members (Morse et al. 2007; Cheruvelil et al. 2014; Pischke et al. 2017). Strong leadership can create a strong identity with the group and a commitment of the team members to the group's aims and goals (Halvorsen et al. 2016). Leaders can also take the role of knowledge

[3]Any citation of SAF21 or ClimeFish in this section implies that the information was extracted from one of the projects.

brokers to support the knowledge integration process. Knowledge brokers should be experts in problem conceptualisation, rhetorically strong, and well-read in multiple disciplines (Arlinghaus et al. 2014).

It is important to employ the right mix of people when setting up an interdisciplinary research team (Arlinghaus et al. 2014). The researchers in the team should want to sit down together with researchers from other disciplines. The researchers should have an open mind and a broad interest, while it also makes it easier to step into other disciplines' concepts if they are widely-read (Paterson et al. 2010). Particularly important is also the ability to re-think one's own values or position when they are being challenged by colleagues from other disciplines. Developing such reflexivity will often require understanding on both the intellectual and personal level (Halvorsen et al. 2016).

Team members should be selected based on strong communication, interpersonal and teamworking skills, high social sensitivity and deep emotional engagement, besides their scientific and technical skills (Castán Broto et al. 2009; Halvorsen et al. 2016). An assessment of researchers culture through e.g. the Hofestede model of cultural dimensions (Hofstede 2011), could reveal additional insights into members' interpersonal strengths and weaknesses. Teams should also aim for high diversity in age, gender, race, and class amongst members to reach better performance (Halvorsen et al. 2016).

- **B3**: *Build and maintain a strong interdisciplinary research team.*

A successful interdisciplinary SES research project requires a strong interdisciplinary team from start to end. As such, establishing a team is just as important as maintaining a team by keeping all team members engaged and committed to the project. Challenges in managing and maintaining interdisciplinary teams can be caused through unequal research responsibilities among the involved disciplines (Lang et al. 2012), and asymmetries between senior and junior researchers that lead to conflicts (Pischke et al. 2017). Conflicts among team members can also be caused through personal conflicts, cultural differences, false expectations on what interdisciplinary work may entail, or arising frustrations among interdisciplinary researchers when lengthy time commitments are required to combine disciplinary data or write interdisciplinary papers (Pischke et al. 2017).

For interdisciplinary teams to be successful, they should aim to have ten essential key char-

acteristics, including: leadership and management, effective communication, personal rewards, training and development, appropriate resources and procedures, appropriate mix of skills and individual characteristics, positive and enabling climate, clarity of a shared vision, quality and outcomes, and respect and understanding (Jacob 2015). For example, personal rewards could be small group gatherings with cake to celebrate the small successes. Training and development can be facilitated in research groups by hiring trainers and through active course participation (ClimeFish 2016; SAF21 2015); a positive and enabling climate can be promoted through support and encouragement by team leaders and colleagues; and quality and outcomes can be achieved through successful integration and documentation of the research.

Team members can be trained in cultural awareness, e.g. through the Hofstede culture compass[4], to better work in international environments with colleagues from different countries and cultures. Training in conflict management can also be provided to ensure that team members learn techniques and methods in how to reduce conflict potential or how to resolve arising issues. In case conflicts arise, these should be solved as close to the problem origin as possible and not involve more people than necessary (SAF21 2015; ClimeFish 2016), and researchers should consider to solve the conflict internally (National Committees for Research Ethics in Norway 2007, paragraph 21).

Team members can also be prepared and trained in advance of conducting interdisciplinary work to create realistic yet flexible expectations among the participants (Gardner et al. 2013). This could entail agreed guidelines for team members, which can facilitate planning and minimise misunderstandings, while also resolving timing and monetary problems (Pischke et al. 2017). Fostering respect and trust among researchers can additionally facilitate communication, and overcome time, logistics, and personal relationship barriers. Trust-building can be achieved by facilitating and designing interactive team-building experiences and exercises that have nothing to do with the research project (Pischke et al. 2017). Face-to-face meetings can also provide the opportunity to foster trust (Bridle et al. 2013), by providing the opportunity to discuss problems and disagreements (Huston 2012). Equally important is the immediate and conscious integration of social and natural scientists into the team to present their efforts as equally valuable (Halvorsen et al. 2016).

[4] https://www.hofstede-insights.com/cultural-survey-pre-paid/

C: Integration phase—How?

- **C1**: *Ensure clear communication.*

Clear communication is crucial for successful integration, as well as the overall execution of the research over the full project lifetime (Jacob 2015). Yet, finding a common vocabulary for communication across multiple disciplines can also create major challenges in interdisciplinary research (Strober 2006; Barlow et al. 2011; Romero-Lankao et al. 2013). Communication is often challenged due to the discrepancies in understanding of concepts and terminology among participants. Therefore, communication can be particularly challenging at the beginning of a project when new modes of communication still have to be developed, when explaining disciplinary concepts (Pischke et al. 2017), finding common ground for problem definitions, and setting up a research plan (Morse et al. 2007; Lang et al. 2012; Brown et al. 2015). Communicating the outcomes and results of the project to a wider audience in a coherent manner can be equally challenging (Morse et al. 2007). The more disparate the disciplines' traditions are from each other, the easier miscommunication occurs (Morse et al. 2007; Lang et al. 2012; Brown et al. 2015; Pischke et al. 2017).

To facilitate communication among researchers from different fields, project specific glossaries and ontologies could be developed early in the project or at the proposal stage. Open encounters also have a positive effect by fostering training in cross-disciplinary communication among participants (Bridle et al. 2013). During these encounters, individual researchers should be both, willing and able, to explain their science in simple words and concepts, while also being open to learn from each other. Feedback questions help to avoid 'disciplinary' misunderstandings.

Research team leaders can additionally facilitate team communication by applying leader communication strategies for which statements should be problem-focused, procedural, socioemotional, and action-oriented (Salazar and Lant 2018).

- **C2**: *Design and conduct interdisciplinary SES study.*

Thorough planning and design of an interdisciplinary SES study is essential to successfully navigate through the complexity inherent to conducting interdisciplinary SES research, on both a scientific, as well as an administrative and organisational level. Differing interdisciplinary practices of researchers can also lead to chaos and confusion, regarding research and publications

protocols, treatments of subjects, data access and availability, roles, authorship or basic etiquette, due to traditions and disciplinary cultures (Bosch and Titus 2009; Pischke et al. 2017).

Interdisciplinary research can also be impeded by resources, most commonly time and money, because, often, more time and money is needed than would be necessary for a similar single disciplinary project (Morse et al. 2007; Pischke et al. 2017). Problematic is also that short-term funding is often not feasible for interdisciplinary projects that require long-term planning and execution.

To better manage the complexity of interdisciplinary SES project, an Interdisciplinary Research Management Framework can be applied in the organisational design of the project, which can help to manage work-flows and to set up functioning structures within the project team (König et al. 2013). This frameworks makes duties of researchers and project managers explicit and enables project set-up in a systematic way.

Also the scope, type and goal of the project is best to be set early and made explicit to all project participants. In particular, to explicitly plan and account for the scope, type and goal of interdisciplinarity, a typology for interdisciplinarity, such as the one by Huutoniemi et al. (2010) can be applied.

An iterative-loop can be incorporated into the project plan to evaluate and re-assess the quality and validity of the results. As such, the first loop of the research process will generate the results, which will then be evaluated. In a second loop, any issues or problems that have been identified with the results can be addressed. After the second loop, results are re-assessed and validated if their quality is satisfying. This loop process allows for an evaluation and for additional time requirements, that are often necessary in interdisciplinary work (ClimeFish 2016). In addition, planning and accounting for high resource needs is important, while also planning for a surplus in budget might be useful to cover unexpected costs in case problems or issues are encountered (Pischke et al. 2017; Bosch and Titus 2009).

- **C3**: *Integration.*

In interdisciplinary research, integration is perhaps among the biggest challenges (Strober 2006; Morse et al. 2007; Gardner et al. 2013; Romero-Lankao et al. 2013). Challenges of integration can occur on many levels, ranging from communicative, organisational, technical, to cognitive. In particular, integrating experimental design, fieldwork plans and data collection have been found

challenging. Sharing and combining information across disciplines can create additional obstacles (Pischke et al. 2017). During integration processes, barriers can occur due to an attachment to one's own discipline, which creates difficulties when aligning research questions and focus across disciplines (Pischke et al. 2017). The lack of detailed plans from the beginning of a project, regarding how and what to integrate, can make the integration process messy and time-consuming (Morse et al. 2007; Barlow et al. 2011; Pischke et al. 2017).

The often difficult integration of social- and natural sciences in SES research can be facilitated by following well-defined processes that lead to effective execution and integration in interdisciplinary research practices. For example, the methodological framework developed by Tobi and Kampen (2018) provides guidance on the conceptual and theoretical design, operationalisation, execution, and integration of interdisciplinary research. The inclusion of a clear study design, data management plans and sampling designs facilitate interdisciplinary integration. In addition, researchers can be trained in methods that allow for an interdisciplinary process and integration in an SES context (SAF21 2015).

Integrative processes commonly contain many interdependencies between tasks, i.e. when one task needs to be fulfilled to address the next task. It can therefore be helpful to map these interdependencies, to highlight where the dependencies lie and with which team members. The interdependencies also represent risks that might hinder project completion. With an interdependency map, these risks can also be identified and risk mitigation strategies can be developed, e.g. what alternatives can be used in case task X cannot be fulfilled (ClimeFish 2016).

Regular and frequent meetings, preferably face-to-face, allow for a generative process that can go beyond parallel play and into integration. Frequent meetings also allow for researchers to germinate and refine their ideas, and to respond as the work evolves, while planning next steps in the research process (Huston 2012).

The connections between interdisciplinarity and creativity have also been explored with the aim to suggest strategies for interdisciplinary researchers. To appreciate interdisciplinary research as a creative thinking process, strategies such as mindfulness practice, meditation and physical exercise could additionally be considered because these practices have been found to enhance creativity (Darbellay et al. 2017). Serious games and live-action role playing can also be used to enhance creativity and stimulate discussions within teams (ClimeFish 2016; SAF21 2015).

- **C4**: *Documentation of interdisciplinary SES research and transferability of results.*

In interdisciplinary studies, the assessment of interdisciplinarity can be difficult if the integration process and outcome are not made transparent and explicit. The evaluation of the performance and quality of the results can also be hard to determine for external reviewers when novel and unfamiliar approaches have been applied. Yet, external evaluation often plays a crucial role for the success of a project and the dissemination of project outcomes, when facing (peer-)review and assessment of publications, grant proposals, and reports. In addition, the conceptualisation of the SES in question, and the theory underpinning the research, often lack reasoning for why a certain theory was chosen and whether it was based on existing theoretical frameworks. This hinders comparison and transferability of the results as such studies can only provide limited case-specific solutions.

To overcome these obstacles, first, a typology of interdisciplinarity (e.g. the typology by Huutoniemi et al. (2010)) can be applied to make the scope, type, and goal of interdisciplinarity explicit. The application of a typology can facilitate the documentation of interdisciplinary research and make the description of the integrative process comprehensible to outsiders. It, thereby, increases the transparency of the research and allows for an easier comparison to other interdisciplinary studies.

For the documentation of research performance and quality, the seven generic principles for interdisciplinary research evaluation by Klein (2008) provide a coherent framework that can be used as a guide. These principles include (1) variability of goals; (2) variability of criteria and indicators; (3) leveraging of integration; (4) interaction of social and cognitive factors in collaboration; (5) management, leadership, and coaching; (6) iteration in a comprehensive and transparent system; and (7) effectiveness and impact. Lyall et al. (2011) also provide practical quality criteria for interdisciplinary research proposals that can provide valuable insights when applying for research grants. These criteria include, for example, that the proposal should indicate the benefits for the disciplines, or the societal and business benefits, that the proposal should justify the interdisciplinary approach and the choice of disciplines. Following principles and quality criteria, such as the ones by Klein (2008) and Lyall et al. (2011), for the documentation of the research can facilitate the evaluation of the quality and performance of the research.

The conceptualisation of the SES and application of any existing theoretical frameworks should

also be made explicit and contain clear reasoning for why a certain theory was chosen (see again Binder et al. (2013) from above). The gained knowledge can then be reintegrated into the literature and with similar studies. Therefore, a comparative study from which generalisable results can be derived and how the study builds on existing frameworks can already be considered when planning the research.

Finally, the practice of open science through open access data and publications and by making code and model simulations openly available increases the transparency of the research. Thus, it enables researchers, reviewers, and evaluators to access the data, re-run analysis and gain insights into the quality of the results and how they were generated. This also allows other researchers to use, replicate and adjust the analysis and to apply it to other case studies (ClimeFish 2016; SAF21 2015).

Table 1 – Design principles for an interdisciplinary SES research process and associated practical challenges with an outline of exemplary practical coping strategies. Sources contain references to challenges. Text in **bold** highlights coping strategies that have been demonstrated in practice through the Papers 1–3 (section 4.2). Text in *italic* highlights existing frameworks that have been incorporated into the coping strategies.

Design principles	Challenges	Description of Challenges	Exemplary Coping Strategies	Sources
A: Orientation phase—'What?'				
A1: State the problem or research question	Lack of guidance for future SES research; Lack of problem awareness	Difficulties to identify research gaps and research priorities in SES domain; lack of problem awareness; Difficulty finding common ground for problem definition	**Conduct pilot study** to build problem awareness; Gap analysis and **assessment of status quo**, mapping with societal challenges; apply *framework for interdisciplinary problem framing*	Morse et al. 2007; Lang et al. 2012; Cumming 2014; Brown et al. 2015; Clark et al. 2017
A2: Consideration of important theoretical elements for the study of SES	Difficulty choosing appropriate theoretical SES framework	Different existing theoretical frameworks and lack of overview; Theory context depended; Frameworks are not comparable	Follow guiding questions for selection of appropriate theoretical framework; Use existing reviews of SES frameworks; Apply criteria to assess theoretical frameworks	Binder et al. 2013; Cumming 2014
A3: Justify and promote benefits of using an interdisciplinary approach	SES theory does not integrate interdisciplinarity; Insufficient support for interdisciplinarity	Underlying SES-theory impedes interdisciplinary approach; Research question does not justify an interdisciplinary approach; Negative perceptions and lack of support for interdisciplinary approach	Apply criteria for identification and justification of an interdisciplinary research question; Select theoretical framework that allows interdisciplinarity; **Assess perceptions of interdisciplinarity**; **Build optimism**; Create awareness for need of interdisciplinarity	National Academy of Sciences 2005; Paterson et al. 2010; Binder et al. 2013; Cumming 2014

Table 1 – continued.

Design principles	Challenges	Description of Challenges	Exemplary Coping Strategies	Sources
B: Preparation phase—'Who?'				
B1: Identify and select relevant disciplines	Weigh disciplinary representation according to research question	Under- or over-representation of disciplines in the research process; Lack of understanding of disciplinary perspectives	Mapping of disciplines (expertise and interests) to SES-theory and research question; Application of competence matrix	Repko 2008; Lang et al. 2012
B2: Identify and select relevant research team members	Lack of team members with the right skill set; Lack of team leaders	Team members lack interpersonal skills and necessary expertise; negative perceptions, disrespect and prejudice towards other disciplines/members; Lack of leadership within the team	Assign skilled inter- and multidisciplinary team leaders and knowledge brokers early in the project; Choose team members with shared goals, and based on their attitudes, expertise and (inter-) personal qualifications	Stokols et al. 2008, Castán Broto et al. 2009; Paterson et al. 2010; Romero-Lankao et al. 2013; Arlinghaus et al. 2014,Halvorsen et al. 2016,Pischke et al. 2017; Salazar and Lant 2018
B3: Build and maintain a strong interdisciplinary team	Lack of trust, legitimacy and commitment; unbalanced team composition	Arising frustrations and conflicts between scientists; Project drop-outs; Conflict due to disciplinary, age, and gender differences; Unequal responsibilities	Pursue key characteristics for successful teams; Specialised training for team members; Solve conflicts close to the problem origin; Create realistic expectations; Team-building exercises and social activities	Schleier and Carver 1993,Stokols et al. 2008,West et al. 2009a,Lang et al. 2012; Jacob 2015; Pischke et al. 2017

Table 1 – continued.

Design principles	Challenges	Description of Challenges	Exemplary Coping Strategies	Sources
C: Integration phase—'How?'				
C1: Ensure clear Communication	Miscommunication	Misunderstandings; Different disciplinary languages; Discrepancy in understanding of concepts and terminology; Difficulty communicating interdisciplinary results	Develop project specific glossaries and ontologies; Open face-to-face encounters; Incorporate feedback questions; Follow good leader communication	Strober 2006; Morse et al. 2007; Barlow et al. 2011; Lang et al. 2012; Gardner et al. 2013; Romero-Lankao et al. 2013; Brown et al. 2015; Pischke et al. 2017; Salazar and Lant 2018
C2: Design and conduct interdisciplinary SES study	Complexity of project; Unstructured approach; Lack of resources	Conflicts over aims and goals; Different expectations among team members; time and money limitations	Follow *framework for interdisciplinary research methodology*; Identify scope, type and goal of interdisciplinarity early in the project; Apply *research management framework*; Incorporate iterative-loop to evaluate and assess quality of the results; Plan and account for high resource needs	Bosch and Titus 2009; Pischke et al. 2017, Tobi and Kampen 2018
C3: Integration	Lack of integration; Lack of clear project and integration management	Lack of research plan; Lack of integrative process; Misunderstandings of what to integrate and how; Unclear processes of who does what and when; Lack of creativity	Follow *framework for integration*; Training in methods that allow for integration; Map interdisciplinary interdependencies; Regular and frequent meetings; Promote and facilitate creative thinking processes	Morse et al. 2007; Barlow et al. 2011; Pischke et al. 2017

Table 1 – continued.

Design principles	Challenges	Description of Challenges	Exemplary Coping Strategies	Sources
C4: Documentation of interdisciplinary SES research and transferability of results	Lack of transparency; Difficulty to assess research quality and performance; Uncertainty of theoretical foundation; Lack of transferability	Integration difficult to identify; Difficulty to evaluate research performance and quality; Choice for theoretical framework unclear or not explicit; Generalisation and comparison of results not possible; Limited case-specific solutions	**Explicit documentation of scope, type and goal of interdisciplinarity**; Explicit and clear reasoning for the choice of theoretical framework underpinning the SES research; Reintegrate generated knowledge into the literature and with similar studies; Practice open science	Huutoniemi et al. 2010; Binder et al. 2013; Cumming 2014

4.2 Demonstration of Selected Coping Strategies

The three Papers 1–3 are demonstrations and practical examples for an application of selected coping strategies suggested in the framework. The papers provide a methodology that can be used to apply a coping strategy and demonstrate what the results may look like when applied to a specific research domain, which is explained in detail below and summarised in Table 2.

Demonstration of A1: Conduct Pilot study, Assessment of Status-quo. The coping strategy A1 is demonstrated in Paper 1 (*Using Machine Learning to Uncover Latent Research Topics in Fishery Models*). Paper 1 demonstrates a methodology to conduct a pilot study as a coping strategy for the design principle **A1**: "*State the problem or research question*". Challenges of this design principle include a lack of problem awareness, difficulties to identify research gaps and an overall lack of guidance for future SES research direction. Paper 1 applies a machine-learning method to conduct a topic analysis of fisheries modelling publications from 1990–2016. The results provide insights into the past and current research trends of the fisheries modelling domain. This analysis exemplifies a methodology that can be used to identify research topics, trends and gaps (for more details see the paper). The approach can serve as a coping strategy in two ways: (1) it can be applied as a **pilot study** that provides empirical evidence to scope the problem and to create problem awareness, e.g. to demonstrate that research trends do not align with research needs to address societal challenges and sustainable development goals; (2) it can be used to assess the **status-quo** within a domain, and to identify if and what topics are not addressed within a research domain. The results can be used to guide future research direction and to state the problem and research question.

Demonstration of A3: Assess Perceptions of Interdisciplinarity, Build Optimism. The coping strategy A3 is demonstrated in Paper 2 (*Interdisciplinary Optimism? Sentiment Analysis of Twitter Data*). Paper 2 demonstrates a methodology to assess perceptions of interdisciplinarity and how to build optimism as a coping strategy for the design principle **A3**: "*Justify using an interdisciplinary approach*". Negative perceptions of interdisciplinarity and lack of support for an interdisciplinary approach can challenge this design principle. Paper 2 identifies perceptions of interdisciplinarity and highlights optimistic opinions. The sentiment

analysis of Paper 2 can be applied as a coping strategy in the following ways: (1) to assess whether there is support for interdisciplinarity on a larger scale, e.g. within a country or city, a wider research community, or within a university or faculty; (2) to identify the audience or cause of negative perceptions of interdisciplinarity in order to target particular negative audiences by creating specific incentives, or by solving the identified causes and problems; (3) to identify the audience and cause of positive perceptions, which can be used to highlight the 'bright spots' of interdisciplinarity to create more interdisciplinary optimism.

Demonstration of C4: Explicit Documentation of Scope, Type and Goal of Interdisciplinarity. The coping strategy C4 is demonstrated in Paper 3 (*An Interdisciplinary Insight into the Human Dimension in Fisheries Models*). Paper 3 demonstrates a methodology that can be applied for the explicit documentation of the scope, type and goal of interdisciplinarity as a coping strategy for the design principle **C4**: "*Documentation of interdisciplinary SES research and transferability of results*". Paper 3 identifies and assesses interdisciplinarity by applying a typology for the scope, type, and goal of interdisciplinarity to a diverse set of fisheries modelling publications. It shows how the application of a typology makes interdisciplinary work more comparable with other studies and therefore allows for an easier re-integration of case studies with the literature.

The method from Paper 3 can be applied as a coping strategies in two ways: (1) the typology can be applied before and during a project to *document* the interdisciplinary scope, type and goal of the research. This will make the interdisciplinary work more accessible, understandable, and transparent; (2) if the documentation of interdisciplinarity is lacking in e.g. a publication or grant proposal, the typology can be applied to *assess* interdisciplinarity. This can make other work more comparable to one's own study. However, proper documentation of interdisciplinarity should always be the primary goal. In particular, because Paper 3 also shows the large efforts required to identify and assess interdisciplinarity when there is a lack of documentation.

Table 2 – Overview of the methodologies and study objects that were used to demonstrate the coping strategies through the Papers 1–3.

Coping strategies	Methods	Study objects
A1: Conduct Pilot study; Assessment of Status-quo; (Paper 1)	- Information retrieval - Web-scraping - Machine-learning - Natural language processing	Fisheries; Models; Topics;
A3: Assess Perceptions of Interdisciplinarity; Build Optimism; (Paper 2)	- Information retrieval - Web-scraping - Opinion mining - Computational linguistics Natural language processing;	Interdisciplinarity; Sentiment; Discourse;
C4: Explicit Documentation of Scope, Type and Goal of Interdisciplinarity; (Paper 3)	- Typology of Interdisciplinarity	Fisheries; Models; Interdisciplinarity;

5 Discussion

5.1 Contribution to Science

The aim of this study is to develop a preliminary framework that can *guide* and *facilitate* interdisciplinary SES research in practice. To achieve that, the framework provides design principles, which can *guide* the research practice by helping researchers understand how to conduct this type of research. The practical challenges in the framework identify what impedes interdisciplinary SES research and the practical coping strategies identify how to prevent and overcome these challenges. Thereby, the challenges and coping strategies *facilitate* interdisciplinary SES research by making the research practice easier and by allowing researchers to gain in-depth insights into the application of the design principles.

The framework development took a pragmatic interdisciplinary approach in, and of, itself, and focused on research practice. Hence, it is difficult to assign the framework to a particular scientific domain, as the framework was not formulated to advance knowledge within one particular field. Instead, the framework is positioned at the interface of interdisciplinary research and social-ecological systems research, while the practical focus also places it into the field of research practices.

Research practices are commonly given through scientific principles that ensure integrity in the research process (National Academy of Sciences 1992). These scientific principles are traditionally very connected with the traditions of science and are mainly conveyed through discussions and informal education. This means that these principles exist primarily in unwritten form, which is why it has been suggested that they should be written down and made explicit (National Academy of Sciences 1992). The scientific principles also differ between disciplines and even within the same discipline, as they are shaped by the procedures of a discipline or a certain field of study (MacLeod 2018). This also explains why it is particularly difficult to conduct interdisciplinary research, since a general interdisciplinary research practice has not been developed as such, while the practices of other disciplines are difficult to access because they exist mainly in unwritten form. Nevertheless, it is possible for interdisciplinary research teams to collaboratively develop their own research practices through a learning-by-doing process (Carr et al. 2018). The literature

suggests that real-world interdisciplinary collaborations are a valuable source to provide insights into what practical approaches for interdisciplinary SES research may look like (Redman et al. 2004). Therefore, the framework in this study followed an approach that tried to access the experiences of empirical case studies reported in the literature, as well as from two EU-funded projects to identify such 'hidden' interdisciplinary research practices. As such, the framework represents a novelty in research practices in general, and in the field of interdisciplinarity in particular, because it provides easy access to interdisciplinary research practices in a written and explicit form. The framework also combines the general (design principles) with the more specific (coping strategies) practices, which is an important trait of scientific principles for research practices (National Academy of Sciences 1992).

The framework also contributes to the literature on interdisciplinary research by providing a coherent overview of important research practices when conducting interdisciplinary work, which was not previously available to this extent. The literature on interdisciplinary research is large and discusses interdisciplinarity in many forms. For example, literature discusses experiences of interdisciplinary scientists (Gewin 2014; Enright and Facer 2016), how to organise, classify, and describe interdisciplinary research (Huutoniemi et al. 2010; Klein 2010; Siedlok and Hibbert 2014), how to conduct and foster interdisciplinary research (National Academy of Sciences 2005; Bruun et al. 2005), how to measure, evaluate and assess interdisciplinary research (Porter and Rafols 2009; Lyall et al. 2011; Wagner et al. 2011; Research Council UK and Digital Science 2016), and how to use it in education (Klein 2006; Davies and Devlin 2010). The many publications of case studies applying an interdisciplinary approach (see, e.g. Kuikka et al. 2011; Levontin et al. 2011; Clark et al. 2017) additionally contribute to this body of literature. Relevant information on interdisciplinary research practices and lessons learned can be found within all these parts of the literature, in addition to interdisciplinary research practices that have been described previously (Castán Broto et al. 2009; Carr et al. 2018; MacLeod 2018), but usually only on the basis of a single case study. Yet, because the literature is rather fragmented and dispersed, it is particularly challenging to draw connections between the different parts of the literature and distil them into a coherent overview on interdisciplinary research practices.

The framework compiles, combines, and integrates the parts of interdisciplinary literature relevant to research practice. It thereby connects these different fragmented branches of literature in

a coherent manner, provides an easily accessible overview, and gives direct references to the particular branches of the literature for readers who wish to know more on a certain topic, including already existing frameworks (König et al. 2013; Clark et al. 2017; Tobi and Kampen 2018).

The framework contributes to the literature on SES research by compiling the different considerations that are important to the study of SES within the literature of SES case studies and theory. The framework also offers novel insights into the interdisciplinary components of SES research in practice, because this is the first time that the principles of SES research are explicitly presented in synthesis with the principles of interdisciplinary research. As such, the framework contributes to the science practice of SES research, rather than SES theory, yet is grounded in theoretical, practical, and empirical aspects of SES research. Hence, the framework contributes to the science of SES through its synthesis of different strands of fragmented SES literature, but also enriches the SES research practice through explicit integration of interdisciplinary research.

The papers demonstrate and operationalise three of the coping strategies in the framework through a practical application of three different methodologies into a research domain. This allows researchers gain insights into what methods can be applied for these particular coping strategies and what type of information the results of such an analysis can provide. Thereby, the papers contribute to: (1) knowledge on what method to use to apply the coping strategy; (2) knowledge on what the results of this method look like in a certain domain; (3) knowledge on what expertise is required to apply this coping strategy and method; and (4) a better understanding of the framework in general.

5.2 Using the Framework—Why, How, and by Whom?

The design principles reflect a generic interdisciplinary SES research process and should be understood as ideal-typical guidelines, rather than instructions for any given context. In addition, the order of the design principles is not strictly determined and depends on the particular research project; some steps of the process may be interdependent. For example, the research question will determine the design of the research project, which will ultimately define which disciplines should be involved.

The practical challenges are highlighted in the framework to increase awareness of these challenges and to allow researchers to put procedures in place to prevent them, or otherwise, overcome them. Depending on when and where the framework is applied, the coping strategies can be used for preventing or addressing challenges. If the framework is applied during the planning stage of a project, the coping strategies can be implemented as preventive measures. If the project is already ongoing and challenges arise during the project, the coping strategies can be applied to solve those challenges. Thus, practical coping strategies facilitate interdisciplinary SES research in practice.

The framework, including the demonstrations through Papers 1–3, can be used by different user groups and applied for different purposes, which are described below and summarised at the end of this section in Table 3.

Researchers. The primary target users of the framework are researchers. Researchers could use this framework during the **proposal writing** stage. Writing grant proposals and applying for funding are very important for interdisciplinary SES work as these types of projects commonly require large funds, often for longer periods (Pischke et al. 2017; ClimeFish 2016). Therefore, the framework could be used and applied during the thinking phase when drafting and designing projects and documenting these plans in a coherent manner and make the evaluation of the proposal easier for the external committee. The coping strategies specified in the framework could be particularly helpful for grant proposals. Calls for proposals now commonly require researchers to specify and describe any critical risks relating to the project implementation and are required to detail any risk mitigation measures[5]. The framework could be applied specifically for the risk section to identify potential practical risks (i.e. challenges) within the project, and could then also provide corresponding mitigation measures (i.e. coping strategies).

Researchers could then further apply the framework when **conducting their research**, in which the design principles could guide their practice, while coping strategies could facilitate the prevention of potential challenges or aid to overcome them if they arise. Papers 1–3 allow researchers to better assess whether any of these three coping strategies will be of value and

[5]See, e.g., section 3.2. in the template from the European Union for H2020 proposals here: https://ec.europa.eu/research/participants/data/ref/h2020/call_ptef/pt/2018-2020/h2020-call-pt-ria-ia-2018-20_en.pdf

whether the methodology and results of the papers are suitable to address or prevent their particular challenge. Researchers can also learn how to apply the coping strategy from the practical examples of the papers. Learning from examples is generally thought to be beneficial to the learning process (Lee and Hutchison 1998; Atkinson et al. 2000). The papers also make it easier to replicate coping strategies and their exemplary methodologies in a different domain.

The framework aims to facilitate research by making interdisciplinary SES research easier in practice, also with the goal in mind to help researchers to use their time more efficiently. Time is often a limiting factor in research, which often leaves researchers stressed and in haste when trying to finish their work within deadlines (Berg and Seeber 2016). Interdisciplinary approaches tend to take even more time when compared to monodisciplinary work (Pischke et al. 2017). For this reason, it is important to use research time well and efficiently. Yet, inadequate preparation for a research project can also easily lead to the wasting of time and thereby dissipate people's goodwill (Bell and Waters 2018). An application of the framework could help with better time management and planning, because it would both guide and facilitate the interdisciplinary SES research process. This means that, for example, researchers spend less time thinking about how to best plan an SES study and there will be less distraction from conflicts because of the prevention through the coping strategies. Hence, the application of the framework could minimise the time spent on challenges and frustrations, and could thereby enhance strategic thinking during research planning and design, while optimising research time.

The framework could further save time by supporting researchers in establishing a common research practice. Commonly, each discipline has its own established research practices, such as the format of meetings or the structure of papers. For interdisciplinary approaches, researchers first have to develop shared research practices, which also takes additional time and effort (Carr et al. 2018). The framework could facilitate this process by creating and providing a baseline for interdisciplinary SES research practice by providing research steps and strategies that can easily be understood and shared across disciplines. Facilitated research practice also creates a lower threshold for interested researchers to get involved and conduct interdisciplinary SES research, and could thus generate a higher uptake of the approach in general.

Consequently, the application of the framework, and the subsequent optimisation of time usage,

could allow for the production of more interdisciplinary SES research within a shorter time, resulting in an overall increase of interdisciplinary SES research output. Integrative research approaches in general (Bruun et al. 2005; Darbellay 2015), and SES research in particular (Österblom et al. 2011; Jerneck et al. 2011), are thought to have high potential for discoveries and innovations supporting sustainability and conservation initiatives. Thereby, an increased SES research output could lead to increased innovation potential and an overall better understanding of SES, which could ultimately help to address many of today's societal challenges, such as climate change, food security, and biodiversity loss (United Nations 2015).

The framework also provides insights into practical skills that may be required from research (e.g. interpersonal skills, team-working skills, etc) to conduct the research. This information could be used by researchers to foster their career development by actively trying to develop these skills through learning-by-doing, or by engaging in targeted training activities to acquire them.

Through the papers, researchers can identify what expertise is required to apply these coping strategies. For example, Paper 1 and Paper 2 both make use of machine-learning techniques. This means that an application of these coping strategies using the methods of Paper 1 and Paper 2 will likely require computer scientists. Having prior knowledge of the skills and expertise requirements for coping strategies allows researchers to plan for these needs in advance, e.g. by inviting in necessary team members.

Transdisciplinary SES Researchers and Practitioners. Transdisciplinary approaches are of great importance in SES research, because they allow the inclusion of stakeholders and practitioners when addressing societal challenges (Guimarães et al. 2018; Haider et al. 2018), and ensure that the 'produced scientific solutions' are of value to the stakeholders (ClimeFish 2016). Notably, researchers working with transdisciplinary SES approaches may also find the framework valuable. According to Liehr et al. (2017), the ideal transdisciplinary research process first involves interdisciplinary integration, which is then followed by transdisciplinary integration. Hence, interdisciplinary integration is an integral part of transdisciplinary practices. Even when researchers have a lot of experience with participatory research, they might lack deeper insights into the interdisciplinary research process. For example, an approach developed by Lang et al.

(2012) provides guidance and advice for transdisciplinary research. Yet, the focus lies mainly on the participatory aspects of the science, and less on the interdisciplinary aspects. In this case, the framework could complement the suggestions by Lang et al. (2012) and provide additional guidance.

Funding bodies and organisations. Funding bodies and organisations, who provide grants for interdisciplinary SES research, are also potential users of the framework, and could apply it in two ways: (i) Funders could recommend that applicants follow the framework when **documenting and describing their research proposal** to ensure that the research process is well designed and that practical challenges are accounted for. This could be particularly relevant for call texts, in which funding is provided to address societal challenges[6], because such calls are likely to include interdisciplinary SES research to some degree (but not always). (ii) Funders could use the framework for the **evaluation process** of grant proposals for interdisciplinary SES research, to assess the quality of the proposed research.

Evaluators and Reviewers. Another potential user of the framework are evaluators and reviewers. The design principles of the framework could be used to **evaluate** grant proposals to check whether an interdisciplinary SES research project is well planned and designed, and if the required coping strategies have been accounted for.
Reviewers could use the framework to evaluate the quality of a study, for example, during peer-review of a publication. The framework could facilitate an evaluation by highlighting the aspects that are important for documentation and that need to be made explicit in interdisciplinary SES research. The criteria for the evaluation of interdisciplinary work by Lyall et al. (2011), which were incorporated into the framework, could help and guide evaluators and reviewers to fairly judge and assess an interdisciplinary SES grant proposal or publication.

Education. The framework could also be used for educational purposes by educators and teachers, but would have to be modified to fit the purpose. For example, the framework could be applied to **teaching** interdisciplinary research practices in higher education or to support

[6] See, e.g., https://ec.europa.eu/programmes/horizon2020/en/h2020-section/societal-challenges.

interdisciplinary courses and programme development. Study programmes that involve more than one discipline are increasing and require necessary interdisciplinary underpinnings (Jacob 2015). Yet, it often remains unclear in interdisciplinary education who, and how, to educate (Hall and Weaver 2001). These answers could be provided (at least in parts) by the framework, e.g. by highlighting necessary **skills** that training could be used for and how to integrate courses. Teaching interdisciplinary research practices to researchers could also increase interdisciplinary interaction, e.g. in doctoral programmes (Carr et al. 2018). As such, the framework could help to overcome the challenges of trying to train the next generation of interdisciplinary scientists (Lyall and Meagher 2012). However, detailed considerations of interdisciplinary education and training are beyond the scope of this study and the framework.

Research domains. Besides an application by different user groups, the framework could also be applied into other research domains that require an interdisciplinary approach. The framework could be adjusted by replacing the design principles and coping strategies concerning SES research with the specific requirements and considerations of the research domain in question. Possible application domains that are inherently interdisciplinary and could benefit from the framework include ethical and responsible research in artificial intelligence (Greene et al. 2019), serious games research (Wilkinson and Matthews 2016), or urban development (Vicenzotti et al. 2016).

Table 3 – Overview of the different potential user groups of the framework and suggestions for applications with an outline of potential benefits. ID = interdisciplinary, SES = social-ecological system.

Users	**Application**	**Benefits**
Primary users and applications		
Researchers	Grant proposals for ID SES research	Facilitates planning and drafting of the project outline; Easier identification of practical risks and mitigation strategies;
	ID SES Research	Guides and facilitates research practice; Optimises project preparation, planning, and research time; Minimises challenges and frustrations;
Researchers and Practitioners	Transdisciplinary SES Research	Optimise integration within transdisciplinary approach;
Funding bodies	Grant proposal templates	Ensures explicit documentation of ID SES research process;
Evaluators	Grant proposal evaluation	Highlights important aspects that need to be considered in ID SES projects; Guides evaluation through explicit criteria;
Reviewers	Peer-review	Facilitates evaluation of quality of a study
Potential users and applications where modifications of the framework are likely required		
Teachers and Educators	Teaching	Facilitates teaching about ID practices; Teaching and training in (interpersonal) skills necessary for ID SES research
	Course development	Facilitates integration during ID course development;
Researchers	ID research domain	Facilitates ID research practice;
	Career development	Highlights skills and training needs;

5.3 Limitations

The framework developed in this study has several limitations:

- Due to limited resources and time restraints, it was not possible to involve relevant user groups in the development process of the framework. The lack of co-creation and involvement of relevant users is a limitation in the methodology of the framework's development. Therefore, this study only serves as a preliminary assessment and a first step towards guiding and facilitating interdisciplinary SES research in practice.

- The framework could not be applied in practice. Hence, whether the design principles can effectively guide interdisciplinary research remains untested. The effectiveness of the coping strategies to prevent and overcome practical challenges with regard to the design principles is also unclear. Yet, many of the coping strategies were identified within empirical case studies, such as Climefish and SAF21. This means that these strategies have already been applied and shown to be of some value, at least in the context of these projects.

- The framework synthesises different strands of literature from interdisciplinary and SES research, but does not claim completeness for the design principles nor provides a complete list of practical challenges or coping strategies. Therefore, some design principles may be lacking, while others might need more detailed consideration. Also, it is likely that there are more practical challenges and coping strategies in the literature that could be added to the framework, but have not been identified at this stage.

- One of the main challenges when working in an interdisciplinary context is integration itself and how to integrate. Integration can be done in many ways, which is why there is not one generic way of doing it and there cannot be a standard solution for how to implement integration (Bruun et al. 2005). Hence, the design principle C3: *Integration* cannot guide integration itself but can only provide ways that can facilitate integration. This is a limitation of the framework.

- Only three of the coping strategies could be demonstrated through the papers with a specific methodology. Hence, the remaining coping strategies lack an example of methodology that could be used for these particular strategies; they also lack examples of an application into a research

domain through a paper. The papers were chosen based on available expertise. Therefore, the selection of the coping strategies and the methodologies for the papers were limited by the available expertise.

5.4 Future Work

Future work to overcome some of the current limitations, and to further develop and improve the framework could include the following:

- The methodology for the framework could be expanded to further develop and validate this preliminary framework through co-creation and the involvement of relevant users. Potential users could apply and test the framework, de-construct it, and re-construct it with possible adjustments and changes, to ensure that it can fit their needs and be used as a practical tool.

- The framework could be tested and validated entirely through an application to a real-world research project, both during the grant proposal stage as well as during the project lifetime. This would allow to identify if and which of the suggested design principles and coping strategies are helpful and those that may need adjustment and improvement.

- Scientific output is produced in large amounts and faster than ever. Therefore, it is likely that the framework will have to be updated with current literature to include recent developments and findings within interdisciplinary and SES research.

- Specific methods and research examples (e.g. papers) should be provided for all the coping strategy (not only three) to further operationalise the framework. Practically, this could be done by adding a column to the framework with suggestions for methodologies that could be applied for each coping strategy. The methods should then be demonstrated in practice, e.g. through publications that have used this approach (as was done with Papers 1–3), or by conducting additional research (e.g. in the form of papers) with additional team members and added expertise. Then, interested researchers would already have a concrete method that they could turn to, or even a study that they could replicate and utilise within their own research project for the application of the coping strategies.

- The framework could be expanded to transdisciplinarity and participatory approaches in SES research, for example, by integrating and building on the work by Lang et al. (2012) on transdisciplinary research principles, and by Newton and Elliott (2016) on how to identify and select relevant stakeholder groups.

6 Conclusions

SES research is important for understanding and addressing some of today's complex problems and societal challenges. Yet, practical barriers often hinder SES research when trying to study SES effectively in an interdisciplinary manner. Therefore, practical guidance on how to conduct such an approach and how to overcome practical barriers is required.

This study has developed a preliminary framework to guide and facilitate interdisciplinary SES research in practice. The framework presents practical design principles for the SES research practice, highlights challenges when applying these practices, and provides practical coping strategies to prevent or overcome these practical challenges.

The review approach of the study highlights how there are many practical lessons to be learned for interdisciplinary SES research from the already existing case studies, projects, and researchers' experiences, which were synthesised in the framework. This synthesis allows for the experiences from individual studies and researchers from different fields to guide and contribute to the practice of SES research. Besides practical guidance, the framework also provides a first overview of key aspects of interdisciplinary SES research in practice, which makes it easier for inexperienced researchers to familiarise themselves with the concepts and practices of both interdisciplinary and SES research.

Selected coping strategies of the framework are demonstrated by providing practical examples of methodologies that could be used to apply these strategies in practice. The framework could be used for different purposes and by different user groups. Researchers and other users are encouraged to apply the framework to explore its benefits, validity, and possibly deconstruct, expand, adjust, or diversify it according to their needs and experiences.

The application of the framework could have many potential benefits, including easier SES research practice, increased SES research uptake, optimised research time, and, perhaps, an increase in SES research studies and output. This could advance interdisciplinary SES research as a field, and ultimately lead to a better understanding of SES in general, and a better understanding of how to address some of today's societal challenges, in particular.

7 Self-Assessment

7.1 Interdisciplinary Communication & Documentation

The study aims to follow the recommendations for communication and documentation that were established in the framework of this study. Therefore, a **glossary** is presented (see page viii) to establish a common set of terms with a clearly defined meaning, and to facilitate interdisciplinary communication. The practice of **open science** is pursued for transparency, replicability, and easier understanding of the approaches developed in the study. Therefore, the code from Paper 1 is available on GitHub[7]. Paper 1 is also published as open access, while the other papers have been submitted to full open-access journals with the intention of also making the data and code available upon publication. The interdisciplinarity in this study is made explicit through **documentation of interdisciplinarity** based on a typology, described below.

Interdisciplinarity in this Study. This study follows an interdisciplinary approach. For the purpose of the framework development, the focus was on empirical interdisciplinarity, which describes research that integrates different kinds of empirical data (Huutoniemi et al. 2010). This approach was applied by extracting and integrating empirical evidence from the literature and from two EU-funded projects to investigate the relationships between interdisciplinarity and SES research in practice.
Papers 1–3 follow the path of methodological interdisciplinarity, whereas 'methods from different fields are combined in order to test a hypothesis, answer a research question, and/or develop a theory' (Bruun et al. 2005, p.84). The term 'method' can refer to both a concrete method or a more general research strategy (Klein 2010).

A taxonomic analysis of interdisciplinarity in relation to this study is provided in the form of a typology. The typology and indicators used to assess interdisciplinarity in this study are based on Huutoniemi et al. 2010 (see Table 4).
Data science was largely involved in this study, which is already an interdisciplinary field on its own (O'Neil and Schutt 2014), combining scientific methods from mathematics, statistics, information

[7] https://github.com/shaheen-syed

science, and computer science, and requiring domain expertise as well as communication and visualisation skills (Hayashi 1998; O'Neil and Schutt 2014). Additional methods were drawn from the fields of medical science (systematic literature review) and social sciences (coding, content analysis, enumeration), and both quantitative and qualitative approaches were applied.

Table 4 – Taxonomic analysis of interdisciplinarity in this study. Typology and indicators according to Huutoniemi et al. 2010. FW=framework, refers to framework developed in this study; SES=social-ecological system

Typology	**Indicator**	**Example**
Scope of Interdisciplinarity - conceptual and cultural distance between the participating research fields)	**narrow** - participating fields are conceptually close to each other	Paper 1 (computer science & fisheries science); Paper 2 (computer science & computational linguistics)
	broad - conceptually diverse fields that cross the boundaries of broad intellectual areas	Paper 3 (fisheries science & social science); FW (interdisciplinarity & SES); This study as a whole
Type of Interdisciplinarity - categories of interdisciplinary interaction differ from each other, such as data or knowledge from different research fields being brought together	**empirical** - different kinds of empirical data are synthesised in a novel, integrated manner	FW
	methodological - different methodological approaches are combined in a novel, integrated manner	Papers 1, 2, 3; This study as a whole
Type of Goals - different interdisciplinary research goals	**epistemological** - intent to increase the knowledge about the research object	Papers 1, 2, 3
	mixed orientation - combination of both kinds of orientation: epistemological and instrumental	FW; This study as a whole

7.2 Personal Reflections

At the beginning of this research, I stood as a biologist. However, this interdisciplinary study required me to study a diverse field of disciplines and domains, including social-ecological systems, interdisciplinary studies, research practices, and fisheries science. In addition, the methodological approach required additional efforts to gain knowledge and understanding in the field of computer science and qualitative methods. It was challenging at times to navigate the different disciplinary theories and practices, especially those of disciplines furthest away from my own, such as the social sciences and humanities. As such, it was also not my intent to dwell on the depths of social science theories and concepts. Nevertheless, this interdisciplinary path has certainly widened my scientific horizons as well as my understanding of other domains, disciplines, and methodologies.

Bibliography

Apostel, Leo, G. Berger, A. Briggs, and G Michaud (1972). *Interdisciplinarity: Problems of Teaching and Research in Universities.* Paris: Organization for Economic Cooperation and Development, p. 323.

Arlinghaus, Robert, Len M Hunt, John R Post, and Micheal S Allen (2014). "Not Fish, Not Meat: Some Guidance on How to Study Fisheries from an Interdisciplinary Perspective". In: *Future of fisheries: perspectives for emerging professionals.* Ed. by WW Taylor, AJ Lynch, and NJ Leonard. Bethesda: American Fisheries Society, pp. 223–230. DOI: 10.13140/2.1.2094.5926.

Atkinson, Robert K., Sharon J. Derry, Alexander Renkl, and Donald Wortham (2000). "Learning from Examples: Instructional Principles from the Worked Examples Research". In: 70.2, pp. 181–214. DOI: 10.3102/00346543070002181.

Barlow, Jos et al. (2011). "Using learning networks to understand complex systems: a case study of biological, geophysical and social research in the Amazon". In: *Biological Reviews* 86.2, pp. 457–474. DOI: 10.1111/j.1469-185X.2010.00155.x.

Bell, Judith and Stephen Waters (2018). *Doing your research project: a guide for first-time researchers.* Maidenhead: McGraw-Hill Education.

Berg, Maggie and Barbara Karolina Seeber (2016). *The slow professor: challenging the culture of speed in the academy.* Toronto: University of Toronto Press, p. 115.

Berkes, Fikret (2011). "Restoring Unity". In: *World Fisheries.* Ed. by Rosemary E. Omner, R. Ian Perry, Kevern Cochrane, and Philippe Cury. Oxford, UK: Wiley-Blackwell. Chap. 2, pp. 9–28. DOI: 10.1002/9781444392241.ch2.

Berkes, Fikret, Johan Colding, and Carl Folke, eds. (2003). *Navigating Social-Ecological Systems.* Cambridge: Cambridge University Press, p. 393. DOI: 10.1017/CBO9780511541957.

Berkes, Fikret and Carl Folke (1998). *Linking Social and Ecological Systems.* Ed. by Fikret Berkes and Carl Folke. Cambridge, UK: Cambridge University Press, p. 476.

Berkes, F et al. (2006). "Globalization, roving bandits, and marine resources". In: *Science* 311.5767, pp. 1557–1558. DOI: 10.1126/science.1122804.

Binder, Claudia R, Jochen Hinkel, Pieter W. G. Bots, and Claudia Pahl-Wostl (2013). "Comparison of Frameworks for Analyzing Social-ecological Systems". In: *Ecology and Society* 18.4, art26. DOI: 10.5751/ES-05551-180426.

Bosch, Xavier and Sandra L Titus (2009). "Cultural challenges and international research integrity". In: *The Lancet* 373.9664, pp. 610–612. DOI: 10.1016/S0140-6736(09)60379-2.

Bridle, Helen, Anton Vrieling, Monica Cardillo, Yoseph Araya, and Leonith Hinojosa (2013). "Preparing for an interdisciplinary future: A perspective from early-career researchers". In: *Futures* 53, pp. 22–32. DOI: 10.1016/j.futures.2013.09.003.

Brown, Bruce (2018). "Interdisciplinary Research". In: *European Review* 26.S2, S21–S29. DOI: 10.1017/S1062798718000248.

Brown, Rebekah R., Ana Deletic, and Tony H. F. Wong (2015). "Interdisciplinarity: How to catalyse collaboration". In: *Nature* 525.7569, pp. 315–317. DOI: 10.1038/525315a.

Bruun, Henrik, Janne Hukkinen, Katri Huutoniemi, and Julie Thompson Klein (2005). *Promoting interdisciplinary research: The case of the academy of Finland*. Vol. 8. 05, p. 206.

Buanes, Arild and Svein Jentoft (2009). "Building bridges: Institutional perspectives on interdisciplinarity". In: *Futures* 41.7, pp. 446–454. DOI: 10.1016/J.FUTURES.2009.01.010.

Carr, Gemma, Daniel P. Loucks, and Günter Blöschl (2018). "Gaining insight into interdisciplinary research and education programmes: A framework for evaluation". In: *Research Policy* 47.1, pp. 35–48. DOI: 10.1016/J.RESPOL.2017.09.010.

Castán Broto, Vanesa, Maya Gislason, and Melf Hinrich Ehlers (2009). "Practising interdisciplinarity in the interplay between disciplines: experiences of established researchers". In: *Environmental Science and Policy* 12.7, pp. 922–933. DOI: 10.1016/j.envsci.2009.04.005.

Cenek, Martin and Maxwell Franklin (2017). "An adaptable agent-based model for guiding multi-species Pacific salmon fisheries management within a SES framework". In: *Ecological Modelling* 360, pp. 132–149. DOI: 10.1016/J.ECOLMODEL.2017.06.024.

Cheruvelil, Kendra S et al. (2014). "Creating and maintaining high-performing collaborative research teams: the importance of diversity and interpersonal skills". In: *Frontiers in Ecology and the Environment* 12.1, pp. 31–38. DOI: 10.1890/130001.

Chiu, Chi Yue, Letty Y.-Y. Kwan, and Shyhnan Liou (2013). "Culturally motivated challenges to innovations in integrative research: Theory and solutions". In: *Social Issues and Policy Review* 7.1, pp. 149–172. DOI: 10.1111/j.1751-2409.2012.01046.x.

Clark, Susan G, Florencia Palis, Garry W Trompf, Timothy M Terway, and Richard L Wallace (2017). "Interdisciplinary problem framing for sustainability: Challenges, a framework, case studies". In: *Journal of Sustainable Forestry* 36.5, pp. 516–534. DOI: 10.1080/10549811.2017.1330213.

ClimeFish (2016). *ClimeFish*. URL: http://climefish.eu/ (visited on 03/08/2018).

Collins, Scott L. et al. (2011). "An integrated conceptual framework for long-term social-ecological research". In: *Frontiers in Ecology and the Environment* 9.6, pp. 351–357. DOI: 10.1890/100068.

Cronin, Patricia, Frances Ryan, and Michael Coughlan (2008). "Undertaking a literature review: a step-by-step approach". In: *British Journal of Nursing* 17.1, pp. 38–43. DOI: 10.12968/bjon.2008.17.1.28059.

Cumming, Graeme S. (2011). *Spatial Resilience in Social-Ecological Systems*. Dordrecht: Springer Netherlands, p. 260. DOI: 10.1007/978-94-007-0307-0.

– (2014). "Theoretical Frameworks for the Analysis of Social-Ecological Systems". In: *Social-Ecological Systems in Transition. Global Environmental Studies*. Ed. by S. Sakai and C. Umetsu. Springer, Tokyo. Chap. Chapter 1, pp. 3–24. DOI: 10.1007/978-4-431-54910-9_1.

Cvitanovic, Christopher and Alistair J. Hobday (2018). "Building optimism at the environmental science-policy-practice interface through the study of bright spots". In: *Nature Communications* 9.1, p. 3466. DOI: 10.1038/s41467-018-05977-w.

Darbellay, Frédéric (2015). "Rethinking inter- and transdisciplinarity: Undisciplined knowledge and the emergence of a new thought style". In: *Futures* 65, pp. 163–174. DOI: 10.1016/j.futures.2014.10.009.

Darbellay, Frédéric, Zoe Moody, and Todd Lubart, eds. (2017). *Creativity, Design Thinking and Interdisciplinarity*. Creativity in the Twenty First Century. Singapore: Springer, p. 214. DOI: 10.1007/978-981-10-7524-7.

Davies, Martin and Marcia Devlin (2010). "Interdisciplinary higher education". In: *Interdisciplinary Higher Education : Perspectives and Practicalities*. Bingley, England: Emerald Group Publishing Ltd. Chap. 1, pp. 3–28.

Dressel, Sabrina, Göran Ericsson, and Camilla Sandström (2018). "Mapping social-ecological systems to understand the challenges underlying wildlife management". In: *Environmental Science & Policy* 84, pp. 105–112. DOI: 10.1016/J.ENVSCI.2018.03.007.

Enright, Bryony and Keri Facer (2016). "Developing reflexive identities through collaborative, interdisciplinary and precarious work: the experience of early career researchers". In: *Globalisation, Societies and Education*, pp. 1–14. DOI: 10.1080/14767724.2016.1199319.

Fang, Jingyun, Guirui Yu, Lingli Liu, Shuijin Hu, and F Stuart Chapin (2018). "Climate change, human impacts, and carbon sequestration in China". In: *Proceedings of the National Academy of Sciences* 115.16, pp. 4015–4020. DOI: 10.1073/pnas.1700304115.

Frank, Roberta (1988). "Interdisciplinary: The First Half Century". In: *Words: For Robert Burchfield's Sixty-fifth Birthday*. Ed. by E.G. Stanley and T.F. Hoad. Cambridge: Brewer, pp. 91–101.

Gardner, Toby A et al. (2013). "A social and ecological assessment of tropical land uses at multiple scales: the Sustainable Amazon Network". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 368.1619, pp. 20120166–20120166. DOI: 10.1098/rstb.2012.0166.

Gewin, Virginia (2014). "Interdisciplinary research: Break out". In: *Nature* 511.7509, pp. 371–373. DOI: 10.1038/nj7509-371a.

Greene, Daniel, Anna Lauren Hoffmann, and Luke Stark (2019). "Better, Nicer, Clearer, Fairer: A Critical Assessment of the Movement for Ethical Artificial Intelligence and Machine Learning". In: *Proceedings of the 52nd Hawaii International Conference on System Sciences*. Grand Wailea, p. 10.

Guimarães, Maria Helena et al. (2018). "Structuring wicked problems in transdisciplinary research using the Social-Ecological systems framework: An application to the montado system, Alentejo, Portugal". In: *Journal of Cleaner Production* 191, pp. 417–428. DOI: 10.1016/j.jclepro.2018.04.200.

Haider, L. Jamila et al. (2018). "The undisciplinary journey: early-career perspectives in sustainability science". In: *Sustainability Science* 13.1, pp. 191–204. DOI: 10.1007/s11625-017-0445-1.

Hall, Pippa and Lynda Weaver (2001). "Interdisciplinary education and teamwork: a long and winding road". In: *Medical Education* 35.9, pp. 867–875. DOI: 10.1046/j.1365-2923.2001.00919.x.

Halvorsen, K. E. et al. (2016). "A case study of strategies for fostering international, interdisciplinary research". In: *Journal of Environmental Studies and Sciences* 6.2, pp. 313–323. DOI: 10.1007/s13412-015-0336-7.

Hart, Chris (1998). *Doing a Literature Review. Releasing the Social Science Research Imagination.* London: Sage Publications.

Hart, Paul J B and John D Reynolds, eds. (2008). *Handbook of Fish Biology and Fisheries.* Vol. 2. Blackwell Publishing, p. 421. DOI: 10.1002/9780470693919.

Hayashi, Chikio (1998). "What is Data Science ? Fundamental Concepts and a Heuristic Example". In: *Data Science, Classification, and Related Methods. Studies in Classification, Data Analysis, and Knowledge Organization.* Ed. by C. Hayashi et al. Tokyo: Springer, pp. 40–51. DOI: 10.1007/978-4-431-65950-1_3.

Hinkel, Jochen, Michael E Cox, Maja Schlüter, Claudia R Binder, and Thomas Falk (2015). "A diagnostic procedure for applying the social-ecological systems framework in diverse cases". In: *Ecology and Society* 20.1, art32. DOI: 10.5751/ES-07023-200132.

Hofstede, Geert (2011). "Dimensionalizing Cultures: The Hofstede Model in Context". In: *Online Readings in Psychology and Culture* 2.1. DOI: 10.9707/2307-0919.1014.

Huston, Aletha C. (2012). "A Path to Inderdisciplinary Scholarship". In: *Interdisciplinary research on close relationships: The case for integration.* Ed. by Lorne Campbell and Timothy J. Loving. Washington DC: American Psychological Association. Chap. 11, pp. 253–272. DOI: 10.1037/13486-000.

Huutoniemi, Katri, Julie Thompson Klein, Henrik Bruun, and Janne Hukkinen (2010). "Analyzing interdisciplinarity: Typology and indicators". In: *Research Policy* 39.1, pp. 79–88. DOI: 10.1016/j.respol.2009.09.011.

Jacob, James W (2015). "Interdisciplinary trends in higher education". In: *Palgrave Communications* 1.1, p. 15001. DOI: 10.1057/palcomms.2015.1.

Jacobs, Jerry A. (2017). "The Need for Disciplines in the Modern Research University". In: *The Oxford Handbook of Interdisciplinarity.* Ed. by Robert Frodeman, Julie Thompson Klein, and Roberto C.S. Pacheco. 2nd. Oxford, UK: Oxford University Press, pp. 35–39.

Jarić, Ivan, Gorčin Cvijanović, Jelena Knežević-Jarić, and Mirjana Lenhardt (2012). "Trends in Fisheries Science from 2000 to 2009: A Bibliometric Study". In: *Reviews in Fisheries Science* 20.2, pp. 70–79. DOI: 10.1080/10641262.2012.659775.

Jerneck, Anne et al. (2011). "Structuring sustainability science". In: *Sustainability Science* 6.1, pp. 69–82. DOI: 10.1007/s11625-010-0117-x.

Klein, Julie Thompson (1990a). *Interdisciplinarity: History, Theory, and Practice*. Ed. by 1. Detroit: Wayne State University Press, p. 331.

– (1990b). "The interdisciplinary process". In: *International research management: studies in interdisciplinary methods from business, government, and academia*. New York: Oxford University Press, pp. 20–30.

– (1996). *Crossing Boundaries: Knowledge, Disciplinarities, and Interdisciplinarities*. Ed. by Ellen Messer-Davidow, David R. Shumway, and David J. Sylvan. 1st ed. Charlottesville: University Press of Virginia, p. 281.

– (2006). "A Platform for a Shared Discourse of Interdisciplinary Education". In: *JSSE - Journal of Social Science Education* 5.April, pp. 10–18. DOI: 10.2390/jsse-v5-i4-1026.

– (2008). "Evaluation of Interdisciplinary and Transdisciplinary Research". In: *American Journal of Preventive Medicine* 35.2, S116–S123. DOI: 10.1016/j.amepre.2008.05.010.

– (2010). "A taxonomy of interdisciplinarity". In: *The Oxford Handbook of Interdisciplinarity*. Ed. by Robert Frodeman. 1st ed. Oxford, UK: Oxford University Press. Chap. 2.

Knoot, T. G., L. A. Schulte, J. C. Tyndall, and B. J. Palik (2010). "The state of the system and steps toward resilience of disturbance-dependent oak forests". In: *Ecology and Society* 15.4, art5.

König, Bettina, Katharina Diehl, Karen Tscherning, and Katharina Helming (2013). "A framework for structuring interdisciplinary research management". In: *Research Policy* 42.1, pp. 261–272. DOI: 10.1016/J.RESPOL.2012.05.006.

Krishnan, Armin (2009). "What are Academic Disciplines? Some observations on the Disciplinarity vs. Interdisciplinarity debate". Southampton.

Kuikka, S, P Haapasaari, I Helle, S Kulmala, and S Mäntyniemi (2011). "Experiences in applying Bayesian integrative models in interdisciplinary modeling: The computational and human challenges". In: *19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty, MODSIM2011* December, pp. 2135–2141.

Lang, Daniel J. et al. (2012). "Transdisciplinary research in sustainability science: practice, principles, and challenges". In: *Sustainability Science* 7.S1, pp. 25–43. DOI: 10.1007/s11625-011-0149-x.

Lee, Adrienne Y. and Laura Hutchison (1998). "Improving learning from examples through reflection." In: *Journal of Experimental Psychology: Applied* 4.3, pp. 187–210. DOI: 10.1037/1076-898X.4.3.187.

Leenhardt, Pierre et al. (2015). "Challenges, insights and perspectives associated with using social-ecological science for marine conservation". In: *Ocean & Coastal Management* 115, pp. 49–60. DOI: 10.1016/j.ocecoaman.2015.04.018.

Leslie, Heather M et al. (2015). "Operationalizing the social-ecological systems framework to assess sustainability." In: *Proceedings of the National Academy of Sciences of the United States of America* 112.19, pp. 5979–84. DOI: 10.1073/pnas.1414640112.

Levin, Simon et al. (2012). "Social-ecological systems as complex adaptive systems: modeling and policy implications". In: *Environment and Development Economics* 18.02, pp. 111–132. DOI: 10.1017/S1355770X12000460.

Levontin, P, S Kulmala, P Haapasaari, and S Kuikka (2011). "Integration of biological, economic, and sociological knowledge by Bayesian belief networks: The interdisciplinary evaluation of potential management plans for Baltic salmon". English. In: *ICES Journal of Marine Science* 68.3, pp. 632–638. DOI: 10.1093/icesjms/fsr004.

Liehr, Stefan, Julia Röhrig, Marion Mehring, and Thomas Kluge (2017). "How the Social-Ecological Systems Concept Can Guide Transdisciplinary Research and Implementation: Addressing Water Challenges in Central Northern Namibia". In: *Sustainability* 9.7, p. 1109. DOI: 10.3390/su9071109.

Liu, Jianguo et al. (2007). "Complexity of Coupled Human and Natural Systems". In: *Science* 317.5844, pp. 1513–1516. DOI: 10.1126/science.1144004.

Lyall, Catherine and Laura R. Meagher (2012). "A Masterclass in interdisciplinarity: Research into practice in training the next generation of interdisciplinary researchers". In: *Futures* 44.6, pp. 608–617. DOI: 10.1016/j.futures.2012.03.011.

Lyall, Catherine, Joyce Tait, Laura Meagher, Ann Bruce, and Wendy Marsden (2011). "A Short Guide to Evaluating Interdisciplinary Research". In: *ISSTI Briefing Note* 9, pp. 1–4.

MacLeod, Miles (2018). "What makes interdisciplinarity difficult? Some consequences of domain specificity in interdisciplinary practice". In: *Synthese* 195.2, pp. 697–720. DOI: 10.1007/s11229-016-1236-4.

Markus, Till, Helmut Hillebrand, Anna-Katharina Hornidge, Gesche Krause, and Achim Schlüter (2018). "Disciplinary diversity in marine sciences: the urgent case for an integration of research". In: *ICES Journal of Marine Science* 75.2, pp. 502–509. DOI: 10.1093/icesjms/fsx201.

McGinnis, Michael et al. (2012). "SES Framework: Initial Changes and Continuing Challenges".

Morse, Wayde Cameron, Max Nielsen-Pincus, Jo Ellen Force, and J.D. Wulfhorst (2007). "Bridges and Barriers to Developing and Conducting Interdisciplinary Graduate-Student Team Research". In: *Ecology and Society* 12.2.

National Academy of Sciences (1992). "Scientific Principles and Research Practices". In: *Responsible Science, Volume I: Ensuring the Integrity of the Research Process*. Washington, D.C.: National Academies Press. Chap. 2. DOI: 10.17226/1864.

– (2005). *Facilitating Interdisciplinary Research*. Washington, D.C.: National Academies Press, p. 306. DOI: 10.17226/11153.

National Committees for Research Ethics in Norway (2007). *Guidelines for Research Ethics in Science and Technology*. Tech. rep.

Newton, Alice and Michael Elliott (2016). "A Typology of Stakeholders and Guidelines for Engagement in Transdisciplinary, Participatory Processes". In: *Frontiers in Marine Science* 3, p. 230. DOI: 10.3389/fmars.2016.00230.

O'Neil, Cathy and Rachel Schutt (2014). *Doing Data Science*. Ed. by Mike Loukides and Courtney Nash. 1st ed. Sebastopol: O'Reilly, p. 407.

Österblom, H. et al. (2011). "Incentives, social-ecological feedbacks and European fisheries". In: *Marine Policy* 35.5, pp. 568–574. DOI: 10.1016/j.marpol.2011.01.018.

Ostrom, Elinor (2007). "A diagnostic approach for going beyond panaceas". In: *Proceedings of the National Academy of Sciences* 104.39, pp. 15181–15187. DOI: 10.1073/pnas.0702288104.

– (2009). "A General Framework for Analyzing Sustainability of Social-Ecological Systems". In: *Science* 325.5939, pp. 419–422. DOI: 10.1126/science.1172133.

Partelow, Stefan (2015). "Key steps for operationalizing social-ecological system framework research in small-scale fisheries: A heuristic conceptual approach". In: *Marine Policy* 51, pp. 507–511. DOI: 10.1016/j.marpol.2014.09.005.

Paterson, B., M. Isaacs, M. Hara, A. Jarre, and C.L. Moloney (2010). "Transdisciplinary cooperation for an ecosystem approach to fisheries: A case study from the South African sardine fishery". In: *Marine Policy* 34.4, pp. 782–794. DOI: 10.1016/j.marpol.2010.01.019.

Pischke, Erin C. et al. (2017). "Barriers and Solutions to Conducting Large International, Interdisciplinary Research Projects". In: *Environmental Management* 60.6, pp. 1011–1021. DOI: 10.1007/s00267-017-0939-8.

Porter, Alan L. and Ismael Rafols (2009). "Is science becoming more interdisciplinary? Measuring and mapping six research fields over time". In: *Scientometrics* 81.3, pp. 719–745. DOI: 10.1007/s11192-008-2197-2.

Pretty, Jules (2011). "Interdisciplinary progress in approaches to address social-ecological and ecocultural systems". In: *Environmental Conservation* 38.02, pp. 127–139. DOI: 10.1017/S0376892910000937.

Ravitch, Sharon M and Matthew Riggan (2012). *Reason & rigor : How conceptual frameworks guide research*. Los Angeles: Sage Publications, p. 174.

Redman, Charles L, J Morgan Grove, and Lauren H Kuby (2004). "Integrating Social Science into the Long-Term Ecological Research (LTER) Network: Social Dimensions of Ecological Change and Ecological Dimensions of Social Change". In: *Ecosystems* 7.2, pp. 161–171. DOI: 10.1007/s10021-003-0215-z.

Rego, Arménio, Filipa Sousa, Carla Marques, and Miguel Pina e Cunha (2012). "Optimism predicting employees' creativity: The mediating role of positive affect and the positivity ratio". In: *European Journal of Work and Organizational Psychology* 21.2, pp. 244–270. DOI: 10.1080/1359432X.2010.550679.

Repko, AF (2008). *Interdisciplinary research: Process and theory*. 2nd editio. Thousand Oaks, California: Sage Publications.

Research Council UK and Digital Science (2016). *Interdisciplinary research: methodologies for identification and assessment*. Tech. rep. London: Digital Science, p. 54.

Rhoten, Diana and Stephanie Pfirman (2007). "Women in interdisciplinary science: Exploring preferences and consequences". In: *Research Policy* 36.1, pp. 56–75. DOI: 10.1016/j.respol.2006.08.001.

Rissman, Adena R. and Sean Gillon (2017). "Where are Ecology and Biodiversity in Social-Ecological Systems Research? A Review of Research Methods and Applied Recommendations". In: *Conservation Letters* 10.1, pp. 86–93. DOI: 10.1111/conl.12250.

Romero-Lankao, Patricia et al. (2013). "ADAPTE: A tale of diverse teams coming together to do issue-driven interdisciplinary research". In: *Environmental Science & Policy* 26, pp. 29–39. DOI: 10.1016/j.envsci.2011.12.003.

Rutting, Lucas, Steph Menken, and Machiel Keestra (2016). *An introduction to interdisciplinary research : theory and practice*. volume 2. Amsterdam: Amsterdam University Press.

SAF21 (2015). *SAF21*. URL: http://www.saf21.eu/ (visited on 03/08/2018).

Salazar, Maritza R and Theresa K Lant (2018). "Facilitating Innovation in Interdisciplinary Teams: The Role of Leaders and Integrative Communication". In: *Informing Science: The International Journal of an Emerging Transdiscipline* 21, pp. 157–178. DOI: 10.28945/4011.

Schleier, Michael F. and Charles S. Carver (1993). "On the power of positive thinking: the benefits of being optimistic". In: *Current Directions in Psychological Science* 2.1, pp. 26–30.

Schmidt, Jan C (2008). "Towards a philosophy of interdisciplinarity. An attempt to provide a classification and clarification". In: *Poiesis und Praxis* 5.1, pp. 53–69. DOI: 10.1007/s10202-007-0037-8.

Scott, Catherine M and Anne T Hofmeyer (2007). "Acknowledging complexity: Critically analyzing context to understand interdisciplinary research". In: *Journal of Interprofessional Care* 21.5, pp. 491–501. DOI: 10.1080/13561820701605474.

Siedlok, Frank and Paul Hibbert (2014). "The Organization of Interdisciplinary Research: Modes, Drivers and Barriers". In: *International Journal of Management Reviews* 16.2, pp. 194–210. DOI: 10.1111/ijmr.12016.

Stephenson, Robert L. et al. (2017). "Practical steps toward integrating economic, social and institutional elements in fisheries policy and management". In: *ICES Journal of Marine Science* 74.7, pp. 1981–1989. DOI: 10.1093/icesjms/fsx057.

Stichweh, Rudolf (1984). *Zur Entstehung des modernen Systems wissenschaftlicher Disziplinen: Physik in Deutschland 1740 - 1890*. Frankfurt am Main: Suhrkamp.

– (2001). "Scientific Disciplines, History of". In: *International Encyclopedia of the Social & Behavioral Sciences*. Elsevier Science Ltd., pp. 13727–13731.

Stokols, Daniel, Shalini Misra, Richard P. Moser, Kara L. Hall, and Brandie K. Taylor (2008). "The Ecology of Team Science". In: *American Journal of Preventive Medicine* 35.2, S96–S115. DOI: 10.1016/j.amepre.2008.05.003.

Strober, Myra H (2006). "Habits of the Mind: Challenges for Multidisciplinary Engagement". In: *Social Epistemology* 20.3-4, pp. 315–331. DOI: 10.1080/02691720600847324.

Szostak, Rick (2013). "The Interdisciplinary Research Process". In: *Case Studies in Interdisciplinary Research*. Thousand Oaks: SAGE Publications, Inc., pp. 3–20. DOI: 10.4135/9781483349541.

Tang, Min and Christian H. Werner (2017). "An interdisciplinary and intercultural approach to creativity and innovation: Evaluation of the EMCI ERASMUS intensive program". In: *Thinking Skills and Creativity* 24, pp. 268–278. DOI: 10.1016/j.tsc.2017.04.001.

Tenza, Alicia, Julia Martínez-Fernández, Irene Pérez-Ibarra, and Andrés Giménez (2018). "Sustainability of small-scale social-ecological systems in arid environments: trade-off and synergies of global and regional changes". In: *Sustainability Science*, pp. 1–17. DOI: 10.1007/s11625-018-0646-2.

Tobi, Hilde and Jarl K. Kampen (2018). "Research design: the methodology for interdisciplinary research framework". In: *Quality & Quantity* 52.3, pp. 1209–1225. DOI: 10.1007/s11135-017-0513-8.

Tress, Bärbel, Gunther Tress, and Gary Fry (2005a). "Defining concepts and the process of knowledge production in integrative research". In: *From landscape research to landscape planning: aspects of integration, education and application*. Ed. by Bärbel Tress, Gunther Tress, Gary Fry, and Paul Opdam. Springer Netherlands. Chap. 2, pp. 13–26.

Tress, Gunther, Bärbel Tress, and Gary Fry (2005b). "Clarifying Integrative Research Concepts in Landscape Ecology". In: *Landscape Ecology* 20.4, pp. 479–493. DOI: 10.1007/s10980-004-3290-4.

United Nations (2015). *United Nations General Assembly: Transforming Our World: The 2030 Agenda for Sustainable Development*. Tech. rep., p. 49.

Van Rijnsoever, Frank J. and Laurens K. Hessels (2011). "Factors associated with disciplinary and interdisciplinary research collaboration". In: *Research Policy* 40.3, pp. 463–472. DOI: 10.1016/j.respol.2010.11.001.

Vicenzotti, Vera, Anna Jorgensen, Mattias Qviström, and Simon Swaffield (2016). "Forty years of Landscape Research". In: *Landscape Research* 41.4, pp. 388–407. DOI: 10.1080/01426397.2016.1156070.

Wagner, Caroline S. et al. (2011). "Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature". In: *Journal of Informetrics* 5.1, pp. 14–26. DOI: 10.1016/j.joi.2010.06.004.

Weingart, Peter and Nico Stehr, eds. (2000). *Practising Interdisciplinarity*. Toronto: University of Toronto Press, p. 294.

West, Bradley J, Jaime L Patera, and Melissa K Carsten (2009a). "Team level positivity: investigating positive psychological capacities and team level outcomes". In: *Journal of Organizational Behavior* 30.2, pp. 249–267. DOI: 10.1002/job.593.

West, C D, C Dytham, D Righton, and J W Pitchford (2009b). "Preventing overexploitation of migratory fish stocks: The efficacy of marine protected areas in a stochastic environment". In: *ICES Journal of Marine Science* 66.9, pp. 1919–1930. DOI: 10.1093/icesjms/fsp159.

Wilkinson, Phil and Thomas Joseph Matthews (2016). "The Serious Games Ecosystem: Interdisciplinary and Intercontextual Praxis". In: *Entertainment Computing and Serious Games*. Ed. by R. Dörner, S. Göbel, M. Kickmeier-Rust, M. Masuch, and K. Zweig. Cham: Springer, pp. 63–91. DOI: 10.1007/978-3-319-46152-6_4.

Paper 1

Using Machine Learning to Uncover Latent Research Topics in Fishery Models.

Syed, S. & Weber, C.T. (2018).

Reviews in Fisheries Science & Aquaculture, 26(3), 319-336.

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Paper 2

Interdisciplinary Optimism? Sentiment Analysis of Twitter Data.

Weber, C.T. & Syed, S.

Under review at *Royal Society Open Science*.

Paper 3

An Interdisciplinary Insight into the Human Dimension in Fisheries Models. A Systematic Literature Review in a European Union Context.

Weber, C.T., Borit, M. & Aschan, M.

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