Governing agricultural land use in an interconnected world:

Opportunities and challenges for Voluntary Sustainability Standards

Inaugural dissertation
of the Faculty of Science,
University of Bern

Presented by

Gabi Sonderegger
from Diepoldsau, SG

Supervisor of the doctoral thesis:

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The Dean
Prof. Dr. Marco Herwegh

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SUMMARY

In today's interconnected world, agricultural land use is influenced by distant drivers and actors, while also having far-reaching sustainability implications extending beyond the boundaries of individual farms. These implications significantly contribute to pressing sustainability challenges, including climate change, biodiversity loss, and social inequalities. Recognizing this, scientists and policymakers increasingly advocate for considering cross-scalar dynamics, including feedbacks and spillovers, to define and govern sustainable agricultural practices. To address this need, the field of land system science has introduced the concept of telecoupling, which provides a framework for conceptualizing, studying, and communicating the intricate social-ecological interactions that influence land use decisions and sustainability outcomes across distant regions.

This dissertation adopts a telecoupling lens to investigate the interface between sustainable agriculture, sustainability governance, and science communication. More specifically, it aims to provide knowledge for 1) developing an integrative and comprehensive approach to conceptualize and operationalize sustainable agriculture in a telecoupled world, 2) a better understanding of the governance of sustainable agriculture within a telecoupled world, and 3) enhancing the communication of scientific knowledge on telecoupling phenomena through visuals. It places a particular focus on the role of Voluntary Sustainability Standards (VSS) in governing spillovers of agricultural land use.

These three objectives are addressed in six research articles, which utilize a combination of synthesis and empirical research methods, including quantitative and qualitative approaches. The presented synthesis research provides foundational knowledge for each objective, by integrating knowledge from various disciplines through (systematic) literature reviews and interdisciplinary workshops. The empirical research involved quantitative analyses of 100 agricultural standards' contents and characteristics, as well as qualitative expert interviews using visual elicitation methods.

In contribution of objective 1, the dissertation highlights that in a telecoupled world, a comprehensive notion of sustainable agricultural land use needs to explicitly consider spillover processes arising from agricultural management practices and leading to impacts beyond the farm in nearby and distant places. It offers practical tools and knowledge to aid researchers and policymakers in this quest, such as a compilation of 21 socio-economic and environmental spillovers of agricultural land use and an analytical framework to assess across scales the sustainability outcomes resulting from changes in agricultural practices.

Spillovers can give rise to scale mismatches in the design of governance interventions, posing common challenges in governing telecoupling phenomena and potentially undermining efforts to promote sustainable agriculture. The dissertation explores the current practice of Voluntary Sustainability Standards (VSS) in governing spillovers (contributing to objective 2). It reveals variations in the extent to which standards regulate spillovers through their requirements. While environmental spillovers are more extensively regulated, socio-economic spillovers appear to receive considerably less attention. The study also identifies additional strategies for standard-setting organizations to integrate spillover perspectives in their standard systems, such rescaling certification activities to the landscape level and expanding the organization's portfolio beyond certification activities. Moreover, it identifies significant barriers to implementing these strategies, which highlight the importance of incorporating spillovers in strategic priority-setting within VSS systems, taking targeted actions at operational levels and employing complementary measures across different governance interventions.

In contribution of objective 3, the dissertation shows the importance of effective science communication in promoting the governance of sustainable agriculture in a highly interconnected world. It demonstrates the potential of visuals as powerful tools for communicating knowledge about complex telecoupling phenomena by employing them in qualitative interviews. The study further explores common practices and challenges associated with visualizing telecouplings, offering practical recommendations for visually communicating such information in an accessible and effective manner.

The dissertation contributes to the field of land system science by providing a foundation for future research and action in governing agricultural land use while considering sustainability implications at both local and global scales. It draws attention to the importance of explicitly considering telecoupling and spillover dynamics when sustainability standards are defined. It provides knowledge that may assist standard-setting organizations in this process, by offering insights into different types of spillovers, current VSS practices in regulating spillovers, and strategies to integrate spillover perspectives into VSS systems. It emphasizes the need for ongoing discussions and research on the nature, relevance and governability of spillovers and the complementary roles of various governance instruments in promoting sustainability across scales. Furthermore, it underscores the significance of effective communication, particularly through visual means, in facilitating dialogues at the science-policy interface to develop effective governance approaches that address the pressing sustainability challenges of our time.

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This PhD has been an unforgettable journey with many unexpected turns, which have greatly shaped my personal and professional path. Conducting a PhD research amid an unfolding pandemic with an uncertain outcome has not always been easy. However, these special circumstances have further highlighted the immense value of the support I have received from my colleagues, friends, and family. I am enormously grateful for the amazing group of people I have had the privilege to meet and have in my life during these past years.

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LIST OF ACRONYMS

AIC	Agricultural intensity change
CDE	Centre for Development and Environment
CITES	Convention on International Trade in Endangered Species
DPSIR	Driving forces-Pressures-States-Impacts-Responses model
EU	European Union
EUE	Ecological unequal exchange
ESP	Ecosystem service provision
FAO	Food and Agriculture Organization of the United Nations
FLEGT	Forest Law Enforcement Governance and Trade (Action Plan of the European Union)
FSC	Forest Stewardship Council
GHG	Greenhouse gas
GIUB	Institute of Geography, University of Bern
GMO	Genetically modified organism
IBER	Income-Based Environmental Responsibility
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
ISEAL	International Social and Environmental Accreditation and Labelling (Alliance)
ITC	International Trade Centre
MAIC	Mechanisms of agricultural intensity change
M & E	Monitoring & Evaluation
NCP	Nature's Contributions to People
NGOs	Non-governmental organization
PNS	Post-Normal Science
RSPO	Roundtable on Sustainable Palm Oil
SAFA	Sustainability Assessment of Food and Agriculture Systems
SDG	Sustainable Development Goals
SEP	Socio-ecological processes
SI	Sustainable intensification
SO	Sustainability outcomes
STDV	Standard deviation
ToC	Theory of Change
UNFSS	United Nations Forum on Sustainability Standards
VSCS	Voluntary sustainability standard spillover coverage score
VSS	Voluntary Sustainability Standards

PART I:

RESEARCH DESIGN AND SYNTHESIS

1. Introduction

1.1 Background

In today's highly interconnected world, the impacts and dynamics of agricultural land use often extend beyond local and national boundaries (Clapp, 2015). For example, local demands for agricultural products are increasingly being met by global supply chains. Hence, drivers of land agricultural land use are increasingly disconnected from places of production (Friis and Nielsen, 2019; Laroche et al., 2020). At the same time, the sustainability implications of agricultural practices can manifest well beyond the farm level (Kissinger et al., 2011). For instance, intensive agriculture involving the application of agrochemicals can result in water pollution downstream, affecting ecosystems and communities in remote regions (Harrison et al., 2019; Sagasta et al., 2017). Moreover, job opportunities in large farms can attract migrant workers from distant economies and societies, creating social and economic implications beyond the local context (King et al., 2021; Rye and Scott, 2018). Agricultural land use thus plays a crucial role in many of the pressing global sustainability challenges of our time (FAO, 2018; IPBES, 2019; IPCC, 2019).

Growing recognition of such interconnectedness among land systems shapes our understanding of current sustainability challenges and guides our efforts to govern them (Eakin et al., 2017; Munroe et al., 2019). Distant drivers of agricultural land use and related processes have thus received growing scholarly attention in recent years (see e.g., Lambin and Geist, 2006; Meyfroidt et al., 2013; Niewöhner et al., 2016; Seto et al., 2012). Similarly, scholars and policymakers alike are highlighting the need to identify and consider the distant implications of land use in sustainability governance. For instance, Pascual et al. (2017) argue that global ecosystem assessments often fail to account for the distant, diffuse and delayed impacts of land use, while Köppel (2019) points to similar shortcomings in project-based impact assessments. Moreover, recent high-level policy reports have emphasized the importance of considering connections between distant places for achieving sustainable development goals (Independent Group of Scientists appointed by the Secretary-General, 2019; IPBES, 2019; Sachs et al., 2020).

In the field of land system science, the concept of telecoupling has gained traction as an approach to investigating and communicating about such distal land use interactions. The telecoupling framework has been proposed for study of socio-economic and environmental interactions across distant regions (Liu et al., 2013). It is intended to help break down complex, globalized land change dynamics into more manageable units of analysis (e.g., 'systems' and 'flows') (Eakin et al., 2014; Friis and Nielsen, 2017a; Liu et al., 2013). The telecoupling concept and its proposed framework are commonly used to investigate sustainable agriculture in an interconnected world (Eakin et al., 2017; Garrett and Rueda, 2019; Rulli et al., 2019). Through the adoption of a telecoupling lens, valuable insights can be gained into the networked dynamics shaping the distant drivers and implications of agricultural land use; thereby, the development of governance strategies that foster sustainable agriculture across different scales can be informed (Eakin et al., 2014; Lenschow et al., 2016).

1.2 Knowledge gaps

Against this background, this section introduces the main knowledge gaps that this dissertation aims to address. They revolve around three main themes: 'telecoupling & sustainable agriculture', 'telecoupling & sustainability governance' and 'telecoupling & science communication'.

Telecoupling & sustainable agriculture

In a telecoupled world, agricultural production affects sustainability across various scales, significantly impacting both the environment and human wellbeing (Levers and Müller, 2019). This occurs through spillover processes that link land use practices or interventions with their impact elsewhere (Meyfroidt et al., 2020, 2018). Examples of spillovers of agricultural land use include both environmental and socio-economic processes, such as nutrient runoff into nearby water bodies through excessive fertilizer use (Andrade et al., 2021; Rashmi et al., 2020), pesticide spray drift beyond the target area (Cech et al., 2023; Linhart et al., 2019), knowledge transfer among farmers (Albizua et al., 2021; Mills et al., 2019) and displacement of small-scale farmers through large-scale commercial agriculture (D'Odorico et al., 2017; Zaehringer et al., 2018).

In a recent article that synthesizes knowledge from the field of land system science, Meyfroidt et al. (2022, p. 4) emphasize that 'managing […] spillover impacts is often more significant than addressing direct impacts'. This highlights the critical role of understanding and addressing the processes that extend sustainability impacts beyond the immediate boundaries of agricultural activities. However, spillovers and their impacts tend to be less visible and less comprehensively understood than on-farm processes and direct impacts (Challies et al., 2019; Meyfroidt et al., 2022). Moreover, a large range of conceptual and disciplinary perspectives exist in spillover research, making it difficult to establish a unified and consistent usage of the term (Lewison et al., 2019; Truelove et al., 2014).

Significant progress has been made recently in terms of conceptualizing land use spillovers (Liu et al., 2018; Meyfroidt et al., 2020) and identifying, characterizing and quantifying them (Deininger and Xia, 2016; Fuller et al., 2019; Heilmayr et al., 2020; Leijten et al., 2021; Pfaff and Robalino, 2017). However, despite these advancements, important gaps remain. Scientists have called for more research on the different mechanisms through which spillovers occur and for the development of tools and methodologies for effectively assessing the relevance of individual spillovers (Liu et al., 2018, 2015; Meyfroidt et al., 2020, 2018). Specifically, to assess and inform the current governance practices of spillovers related to sustainable agriculture, further efforts to conceptualize and operationalize spillovers of agricultural land use are needed. This entails a comprehensive overview of spillover processes and their consequences across multiple scales, taking into consideration the environmental, social and economic dimensions. Existing research has primarily focused on investigating individual spillovers of agricultural land use or a subset thereof (see e.g., Blitzer et al., 2012; Lewis et al., 2011; Plowright et al., 2021; Tscharntke et al., 2005; Xia and Deininger, 2019; Zimmerer et al., 2018). There is thus a clear need for integrated frameworks geared towards synthesizing knowledge from various disciplines and providing a holistic and comprehensive approach to sustainable agriculture in a telecoupled world.

Telecoupling & sustainability governance

To foster sustainable agriculture within a telecoupled world, effective governance interventions are essential. However, existing research has highlighted the complexities and various challenges associated with governing telecoupling phenomena toward sustainability, including diverging interests and power asymmetries among distantly located actors, high transaction costs for cross-border collaboration, and policy incoherence (Challies et al., 2019; Munroe et al., 2019; Newig et al., 2020; Oberlack et al., 2018).

Many of these challenges stem from issues of scale (Challies et al., 2019). Spatial scale mismatches, in particular, pose a significant challenge in relation to agriculture (Pelosi et al., 2010). They indicate situations where the spatial scale of governance interventions are not aligned with the scale of the sustainability impacts they seek to address (Cumming et al., 2006). As spillovers are frequently disregarded in the design of governance interventions, they can contribute to such misalignments and undermine their effectiveness (Liu et al., 2018). Existing research calls for a better understanding of current governance efforts targeting telecoupling phenomena, including the development of approaches that can effectively bridge spatial gaps (Challies et al., 2019; Lenschow et al., 2016). As suggested by Cotta et al. (2022), adopting a problem-centered approach is thereby essential. This approach entails first identifying the pertinent telecoupled dynamics and their adverse sustainability impacts across distances and then assessing the extent to which existing governance interventions address these dynamics (as opposed to focusing only on the interventions and their governance range).

Voluntary Sustainability Standards (VSS), also often referred to as certification schemes or eco-labels, are private governance interventions frequently discussed in the context of telecoupling governance and sustainable agriculture (Eakin et al., 2017, 2014; Lenschow et al., 2016). They, along with other supply chain initiatives (e.g., company pledges or codes of conduct), have emerged to govern supply chain flows where public instruments have limited spatial reach (Byerlee and Rueda, 2015; Lambin et al., 2018). Despite implementation challenges and mixed results on the ground (see e.g., DeFries et al., 2017; Dietz et al., 2022; Meemken et al., 2021; Oya et al., 2018), VSS remain popular instruments to define and promote sustainability practices in agriculture (ITC, 2021; OECD, 2022).

Newig et al. (2019) propose three perspective on governance and telecoupling interactions: governance can 1) *coordinate* telecoupling flows, 2) *induce* telecouplings, or 3) *respond* to telecouplings. VSS play a role in all three aspects. They shape and coordinate telecoupling flows along the agricultural supply chain, induce spillovers impacting sustainability beyond their immediate scale of intervention, and respond to telecoupling dynamics by incorporating negative externalities or spillovers into their standards. However, existing research on VSS and telecoupling has predominantly taken the first perspective, discussing VSS in terms of their ability to *coordinate* and regulate supply chain flows (Eakin et al., 2014; Munroe et al., 2019; Newig et al., 2020; Sikor et al., 2013). For instance, researchers have investigated how VSS link and influence different actors along the supply chain (e.g., producers and consumers) through flows of information (Carrasco et al., 2017; da Silva et al., 2019; Marola et al., 2020). Research exploring the potential of VSS to *induce* telecoupling dynamics with implications for sustainability beyond their main scale of intervention is, however, limited (besides Heilmayr et al., 2020). Furthermore, the *response* of VSS to telecoupling dynamics (e.g., by regulating them through their standard requirements) has also received little attention in scientific literature.

While VSS operate along supply chain flows, their implementation is primarily place-based. VSS requirements typically outline actions at the farm level, and therefore, their compliance is also assessed at that level. However, there are knowledge gaps concerning the extent to which VSS regulate spillovers from agricultural land use that extend beyond their primary scale of intervention. Investigating these knowledge gaps could help to identify potential spatial scale mismatches in the design of VSS and develop strategies to tackle them. Therefore, further research is needed to examine the current practices, as well as the opportunities and challenges for VSS in addressing spillover processes and their sustainability impacts across different scales.

Telecoupling & science communication

In the pursuit of effective governance for sustainable agriculture beyond scale, the significance of fostering an engaged dialogue between academia and practitioners has emerged as a central theme (Dinesh et al., 2018; Zeigermann, 2021). Clear and impactful communication of scientific knowledge on telecoupling phenomena is therefore key. As policymakers are increasingly recognizing the importance of adopting a telecoupling lens to govern sustainability challenges, it is essential to establish effective mechanisms for communicating the produced scientific knowledge in an accessible and practical manner to both the scientific and non-scientific audience. While many scientific efforts have focused on applying the telecoupling framework in specific contexts (see e.g., Hulina et al., 2017; Liu et al., 2014; Waloven et al., 2023), relatively little attention has been paid to communicating the results of telecoupling research. While the translation of scientific evidence into accessible and actionable information for informing decision-making is a challenge for any discipline, it can be particularly demanding for research that deals with complex, uncertain and multi-dimensional dynamics (Arnott and Lemos, 2021; Fischhoff and Davis, 2014; von Winterfeldt, 2013; Watson, 2005). Effectively communicating the knowledge generated from telecoupling research, which often addresses intricate and multi-scalar land change dynamics, remains a challenge (Zaehringer et al., 2019).

Visualizations can play a key role in the process of sharing scientific information in the science-policy-society nexus (Grainger et al., 2016; Lorenz et al., 2015; McInerny et al., 2014). They are powerful tools for engaging users with unfamiliar, complex or intangible concepts (Lima, 2011; McInerny, 2013). In the field of land system science, visual representations have been widely used to conceptualize and analyse telecoupling phenomena and to communicate research findings within and beyond the scientific domain. For instance, spatially explicit tools have been developed or used to identify and map components of the telecoupling framework (Kacaw and Tsai, 2023; McCord et al., 2018; Tonini and Liu, 2017). Despite the widespread use of visuals in the telecoupling research community, there are knowledge gaps in the visual communication of scientific knowledge on telecoupling phenomena. Producing accessible and unbiased visuals from complex subject matters is challenging and requires an informed and carefully reflected visualization design process (Grainger et al., 2016; McInerny et al., 2014). A comprehensive understanding and clear guidelines for visualizing telecoupling dynamics are, however, lacking, along with reflection on the underlying assumptions and potential biases associated with visual design (Banitz et al., 2022; Spiegelhalter et al., 2011). Furthermore, the exploration of novel and innovative approaches to communication, such as the use of visualizations and engaging dialogue between academia and practitioners, is crucial to enhance the understanding and application of telecoupling concepts in real-world contexts (Zaehringer et al., 2019).

1.3 Research objectives

This dissertation addresses the knowledge gaps identified in the previous section through three primary research objectives, as outlined in Figure 1. These three objectives are interconnected. Objective 2 provides the central theme of this dissertation, aiming to contribute knowledge on the effective governance of sustainable agriculture in a telecoupled world. Specifically, it focuses on spillovers of agricultural land use and their governance through sustainability standards. Objective 1 contributes to this objective by providing the conceptual foundations on sustainable agriculture in a telecoupled world, which are then used to investigate current practices of VSS in governing spillovers. Objective 3 serves to generate knowledge that facilitates communication on telecoupling phenomena at the science-policy-society interface, both within and beyond the scope of this dissertation.

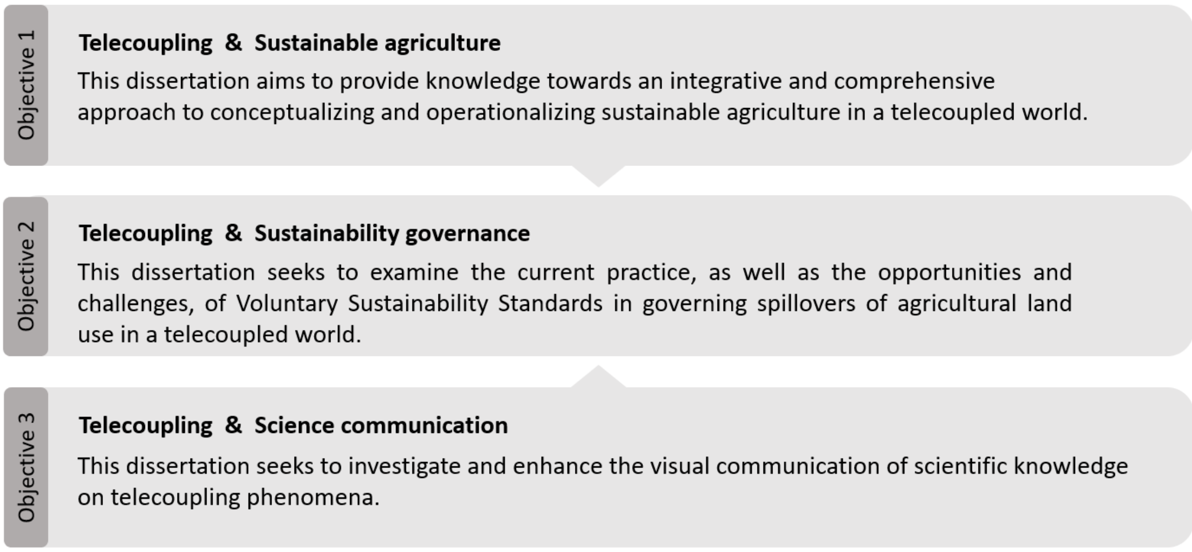

Figure 1: Research objectives

2. Research approach and methodology

2.1 Overview of research articles

This dissertation presents the following six scientific articles.

Nr.	Article title	Authors	Journal	Status
I	Developing context-specific indicator frameworks for sustainability assessment of agricultural intensity change: an application for Europe	Diogo V, Helfenstein J, Mohr F, Varghese V, Debonne N, Levers C, Swart R, **Sonderegger G**, Nemecek T, Schader C, Walter A, Ziv G, Herzog F, Verburg P, Bürgi M	Environmental Science and Policy	Published (2022)
II	Towards spatial fit in the governance of global commodity flows	Coenen J, **Sonderegger G**, Newig J, Meyfroidt P, Challies E, Bager SL, Busck-Lumholt LM, Corbera E, Friis C, Pedersen AF, Laroche PCSJ, Parra Paitan C, Qin S, Roux N, Zähringer JG	Ecology & Society	Published (2023)
III	Why telecoupling research needs to account for environmental justice	Boillat S, Martin A, Adams T, Daniel D, Llopis J, Zepharovich E, Oberlack C, **Sonderegger G**, Bottazzi P, Corbera E, Ifejika Speranza C, Pascual U	Journal of Land Use Science	Published (2020)
IV	Governing spillovers of agricultural land use through voluntary sustainability standards: a coverage analysis of sustainability requirements	**Sonderegger G**, Heinimann A, Diogo V, Oberlack C	Earth System Governance	Published (2022)
V	Telecoupling visualizations through a network lens: a systematic review	**Sonderegger G**, Oberlack C, Llopis JC, Verburg P, Heinimann A	Ecology & Society	Published (2020)
VI	Fostering sustainable agriculture beyond the farm level: entry points and barriers for voluntary sustainability standards	**Sonderegger G**, Heinimann A, Oberlack C		Submitted

Table 1: List of scientific articles presented in this dissertation

2.2 Research design

The six scientific articles collectively contribute to addressing the dissertation's three objectives (see Figure 2). Article I investigates how changes in agricultural practices affect sustainability outcomes at different scales, providing knowledge for operationalizing sustainable agriculture within a telecoupling context (objective 1). Articles II and III focus on identifying and discussing telecoupling governance challenges, particularly those related to spatial scale misfits and environmental justice, thereby contributing to objective 2. Building upon these findings, Article IV delves into the governance of sustainable agriculture in a telecoupling context, with a specific emphasis on examining spillovers of agricultural land use and voluntary sustainability standards (addressing objectives 1 and 2). This article particularly focuses on addressing challenges associated with a specific type of scale mismatches known as boundary mismatches (as identified in Article II). Article V explores effective visual communication of telecoupling knowledge, thus making a significant contribution to objective 3. Finally, Article VI integrates the insights derived from previous studies, utilizing visualizations to investigate how sustainability standard systems can be transformed to foster sustainability beyond the farm level (contributing to objectives 2 and 3).

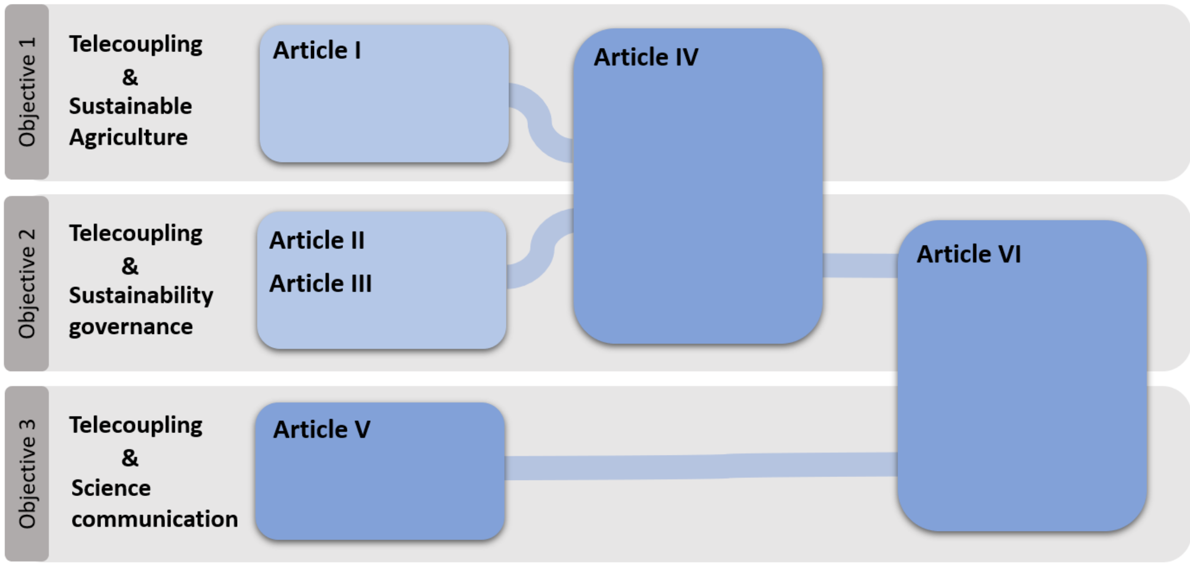

Figure 2: Overview of research articles and their contribution to the research objectives. First authored articles are marked in dark blue, co-authored articles in light blue.

2.3 Methodological approach

This PhD research employs an integrative research design that combines synthesis and empirical research and makes use of both quantitative and qualitative methods. Figure 3 presents an overview of the different methods used and indicates how they contribute to the research objectives. It shows that this dissertation presents a combination of synthesis and empirical research, with the synthesized knowledge informing the empirical research. The following sections provide more information about the methodological approaches used in this study. A more detailed account is provided in the different research articles and their Appendices.

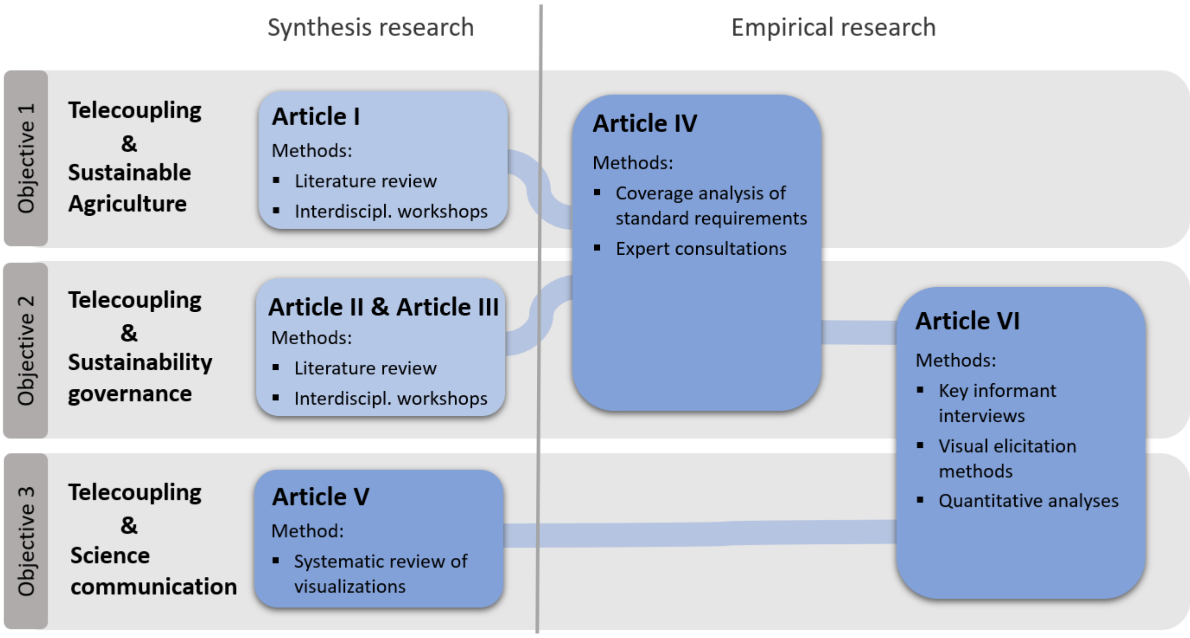

Figure 3: Methodological overview of research articles. First authored articles are marked in dark blue, co-authored articles in light blue.

Synthesis research

Synthesis methods are commonly used in the field of land system science, e.g., to integrate research contributions on land use change in different localities and on different scales (Magliocca et al., 2018, 2015; van Vliet et al., 2016). Synthesis research can be used to integrate and distil evidence from disciplinary and methodologically diverse sources (Magliocca et al., 2015). It is particularly useful in the context of telecoupling research, as the telecoupling framework is designed to integrate knowledge from different disciplines (Friis et al., 2016; Liu et al., 2013). Several comprehensive review studies have been conducted on telecoupling research, synthesizing both research practice and content (Busck-Lumholt et al., 2022; Corbera et al., 2019; Cotta et al., 2022; Kapsar et al., 2019).

For this study, my article co-authors and I conducted synthesis research that contributed to each of the three research objectives (see Figure 3). It served to integrate knowledge from various disciplines and research practices in order to provide an overarching understanding of the links between telecoupling and the themes of sustainable agriculture, sustainability governance and visual science communication. For Article I, a comprehensive, stepwise literature review for informing sustainability assessments of agricultural practices, taking account of the telecoupling context, was conducted. Furthermore, two literature reviews were performed in order to inform the interface of telecoupling and sustainability governance, drawing on insights from environmental governance literature on scale mismatches (Article II) and environmental justice scholarship (Article III).

We also conducted a systematic review that synthesized existing knowledge about the use of visuals in order to communicate telecoupling research (Article V). Systematic reviews involve a systematic search, appraisal and synthesis of scientific evidence, allowing an assessment of the current state of knowledge or practice in a field of research (Grant and Booth, 2009; Petticrew and Roberts, 2006). We systematically selected and reviewed 118 visualizations presented in 62 scientific articles on telecoupling. Our study was particular in the sense that we did not review the text provided within the articles, but rather their visualizations. We applied a network perspective to code and analyse these articles in terms of their visualization content and adopted visualization techniques. This synthesizing approach allowed us to develop a comprehensive understanding of the way visuals are used in the telecoupling research community and to identify opportunities for improving the current practice.

Empirical research

Building on the knowledge derived from synthesis research, we conducted empirical research in order to address our research objectives further. We applied this to the case of Voluntary Sustainability Standards (VSS) and combined quantitative and qualitative research methods.

We used quantitative methods to generate empirical evidence about the inclusion of telecoupling dynamics in VSS contents (Article IV) and practice (Article VI), based on a large sample of VSS. To do so, we used data from the Standards Map database of the International Trade Centre (ITC). The Standards Map (https://standardsmap.org/) provides extensive information on more than 300 sustainability standards in the fields of sustainable trade and production (ITC, 2023). The platform aims to support practitioners in navigating and understanding the dynamic landscape of sustainability standards. We used this database as it is the most comprehensive and standardized dataset on sustainability standards. It contains 1,650 variables per standard; these provide detailed information about the standards' content, as well as the characteristics and performance of the overall standard systems. Furthermore, the database is frequently updated, with the data collection process applying a defined procedure that involves checks by external experts and interactions with the respective standard organizations. Collaborative exchanges with the team managing the database facilitated the adequate use and correct interpretation of the data.

For Article IV, we performed a coverage analysis of VSS contents in order to assess the extent to which standards regulate processes affecting sustainability beyond the farm level (see Bissinger et al., 2020; Blankenbach, 2020; Dietz et al., 2018; Elder et al., 2021; Potts et al., 2014 for similar methodological approaches). We analysed data on the detailed contents of 100 agricultural VSS, focusing on their coverage of 21 environmental and socio-economic spillovers of agricultural land use (see section 3.2 for information about the concept of 'spillovers'). To this end, we coded 445 VSS content categories, then aggregated the relevant ones and calculated the VSS coverage for individual spillovers (see Article IV in Part II for more details). In addition, we analysed ITC data regarding the characteristics of VSS systems (e.g., on standard-setting procedures, stakeholder participation and verification mechanisms) to reveal insights into current practice in VSS systems (see Articles IV and VI).

We further conducted expert consultations (Article IV) and qualitative online interviews with key experts on VSS and representatives of standard-setting organizations (Article VI). These semi-structured interviews were conducted online between July 2021 and April 2022. They served to provide insights on existing VSS practice and to produce transdisciplinary knowledge about entry points and barriers in terms of integrating spillover perspectives into VSS systems. We used visual elicitation methods to stimulate and structure the interview discussions (Bagnoli, 2009; Bravington and King, 2018; Crilly et al., 2006; Salmons, 2016). To this end, we developed visualizations that were intended to facilitate communication with our respondents about the rather abstract and, to them, still unknown concepts of 'telecoupling' and 'spillovers'. We thereby drew on insights gained from the previous systematic review study on telecoupling visualizations (Article V). We then used other graphics as visual stimuli and a guiding frame for the interview section on entry points and barriers. Interview questions directly related to the content of the presented visuals. Furthermore, the respondents actively contributed to knowledge creation by sharing feedback and suggestions regarding the visualization content and design. We thus developed the visuals using an iterative process, continuously adjusting them based on newly received expert input.

2.4 Limitations

In this section, I discuss some of the limitations of the chosen research design and methodological approaches employed in this study. More specific limitations associated with the data and methodologies used in the individual research articles are outlined in Part II of the dissertation.

First, it is important to note that the COVID-19 pandemic has significantly affected the research design by considerably limiting the possibilities for conducting fieldwork (see Box I). As a result, the research design did not incorporate qualitative, on-the-ground investigations that would have otherwise contributed to research objective 1, as originally planned. Alternatively, this dissertation focused on generating generalized knowledge regarding the conceptualization and operationalization of sustainable agriculture in a telecoupled world, based on the review of existing literature and expert consultations (see Article I and IV). In principle, this knowledge could then be applied to investigate a variety of contexts. However, research is still needed to refine and test the validity and applicability of the proposed concepts and methodological approaches in specific contexts.

Moreover, while this study emphasizes the importance of prioritizing spillovers in a governance context, it does not necessarily prescribe which types of spillover are the most relevant to be governed. This is a deliberate omission, given that not only the relative importance of different types of spillover processes is highly context-dependent (e.g., depending on their specific social-ecological features), but also because I endorse that such decisions should be taken within the context of deliberative processes involving local actors and relevant stakeholders. Nevertheless, the insights presented regarding the conceptualization and operationalization of sustainable agriculture aim to lay a foundation for informing future scientific advancements and societal debates in this direction.

Finally, it is important to acknowledge that the empirical research conducted for objective 2 had a relatively limited scope, focusing solely on a single governance instrument, i.e., VSS. Similarly, the insights provided on the communication of scientific knowledge regarding telecoupling phenomena primarily focused on visual communication. I chose to concentrate on prominently used instruments and considering the large sample sizes in both cases (a significant share of existing agricultural VSS in Article IV and all relevant telecoupling visualizations in Article V), I am confident in the generalizability of the results within the selected scope of this research. However, further research is crucial to explore the role of other governance instruments and alternative communication tools in the context of telecoupling.

Box I – Study context: COVID-19 pandemic and its effects on the study design and methods

This study was largely conducted during the COVID-19 pandemic, with official travel restrictions and limitations regarding personal interactions in place from spring 2020 until the end of 2022. These circumstances largely affected the research design and methodological choices. Initially, it was planned that this dissertation research would involve intensive case study research in Laos on spillovers related to coffee production and the governance thereof. However, the first lockdowns hit the world in the week of the planned start of my field trip to Laos. Uncertain times followed, with continued restrictions, resulting in an eventual realization that fieldwork would not be possible within the timeframe of the study. Consequently, we had to adjust the research content and design considerably, primarily focusing the empirical component of the dissertation on the analysis of secondary data. Furthermore, we used qualitative online interviews to collect primary data for Article VI.

3. Conceptual approach

This dissertation is situated in land system science, an interdisciplinary and integrative field of study focusing on socio-ecological land systems (Verburg et al., 2013). In particular, it draws on two concepts prominently used in land system science to research interactions among land systems: 'telecoupling' and 'spillovers' (Meyfroidt et al., 2022; Verburg et al., 2015). Both concepts serve to analyse nearby or distal linkages between land systems (thereby predominantly focusing on geographic distance). However, they differ in their analytical focus and approach. While the telecoupling concept and its proposed framework allow scholars to conduct comprehensive analyses of interconnected land systems, the spillover concept is better suited for analyzing specific systems or flows and the processes through which they impact nearby or distant land systems (Liu et al., 2018, 2013; Meyfroidt et al., 2020).

This dissertation uses both concepts in a complementary way (see Figure 4). In Articles III and V, telecoupling serves as a heuristic lens to explore the research and communication of phenomena related to distal linkages among land systems. Article II investigates the governance challenges for telecoupling phenomena, thereby pointing to spillovers as key mechanisms driving those challenges. In Articles I and IV, we apply the spillover concept to identify the processes through which farm-level activities impact sustainability in nearby and distant places. Additionally, we examine the role of VSS in addressing spillovers, as presented in Articles IV and VI.

In the following sections, I introduce the two concepts in more detail. I present their distinct conceptualizations and applications within the field of land system science, while also outlining their specific application in this dissertation.

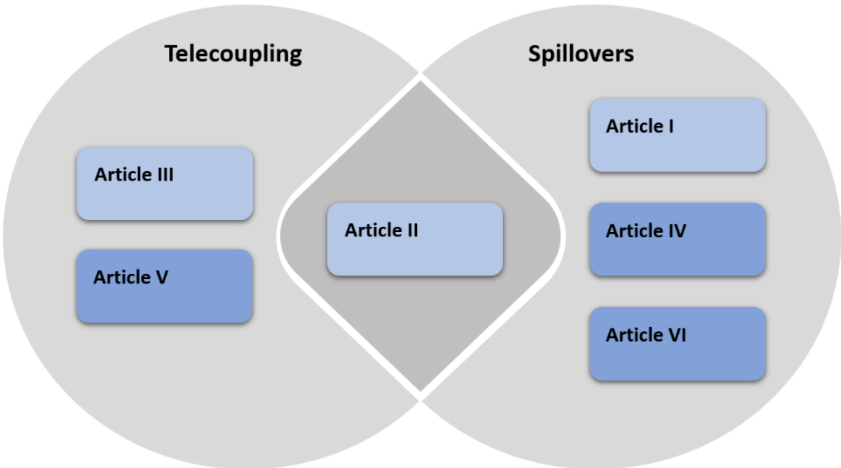

Figure 4: Conceptual overview of research articles. First authored articles are marked in dark blue, co-authored articles in light blue. Design by PresentationGO.

3.1 Telecoupling

Telecoupling is an umbrella concept that offers a framework to investigate the complex, multi-scalar and multi-actor processes that affect land change (Eakin et al., 2014; Liu et al., 2013). Telecoupling phenomena refer to socio-economic and environmental interactions over distance (Liu et al., 2019, 2013). By integrating perspectives from both place-based and flow-based approaches, and incorporating insights from actor-network research, the concept of telecoupling facilitates a dynamic and interdisciplinary analysis of the interconnected relationships between socio-ecological systems across distant locations (Eakin et al., 2014; Friis and Nielsen, 2017b; Liu et al., 2013).

Over the past decade, the telecoupling concept has gained significant traction across diverse disciplines, serving as a promising framework for understanding and analysing a wide range of distal human-environment interactions (Hull and Liu, 2018; Kapsar et al., 2019). Examples include transnational land deals (Friis and Nielsen, 2017b; Oberlack et al., 2018; Rulli et al., 2019), international conservation efforts (Carmenta et al., 2023; Kuemmerle et al., 2019; Persson et al., 2022) and the soybean trade (Garrett et al., 2013; Gasparri et al., 2016; Silva et al., 2017). Moreover, in alignment with the focus of this dissertation, numerous studies have employed the concept of telecoupling to investigate agricultural production and value chains (see e.g., Eakin et al., 2017, 2009; Friis and Nielsen, 2017b; Garrett and Rueda, 2019; Rulli et al., 2019; Zimmerer et al., 2018).

Friis et al. (2016) have identified two main approaches in existing telecoupling research. First, some studies have adopted a more structured application of the telecoupling framework as presented by Liu et al. (2013). In these studies, the various components of telecouplings – including systems, flows, agents, causes and effects – are systematically identified and analysed. Secondly, telecoupling has also been employed as a heuristic tool in certain studies. As a heuristic, telecoupling serves as an analytical lens that allows land use scientists to identify and capture the cross-scalar and networked interactions that influence and are influenced by local land use phenomena (Eakin et al., 2014). In the context of this dissertation, the telecoupling concept will be utilized as a heuristic. By adopting this approach, we have employed telecoupling as an analytical lens to investigate agricultural land use phenomena and their implications beyond the farm level. Moreover, we have examined governance approaches that aim to foster sustainability within this context.

3.2 Spillovers

The scientific contributions of telecoupling research have brought attention to the spillover concept in land system science (Eakin et al., 2014; Liu et al., 2018, 2013). In the Collins English Dictionary, the word 'spillover' is defined as follows: 'A spillover is a situation or feeling that starts in one place but then begins to happen or have an effect somewhere else' (Collins Dictionary, 2021). Fundamentally, spillovers are thus causal mechanisms that link two distinct places. Yet the definitions and uses of the concept vary widely, as it is used in a large variety of scientific fields, ranging from health sciences (e.g., on disease spillovers (FAO et al., 2020; Plowright et al., 2021; Power and Mitchell, 2004)) to business psychology (e.g., on knowledge spillovers of entrepreneurship (Acs et al., 2013; Lattacher et al., 2021)) and sociology (e.g., on social movement spillovers (Meyer and Whittier, 1994)). In addition, a range of related concepts also refer to cross-scalar processes and their impacts (e.g., externalities, spatial slippage and displacement processes). Article IV presents an overview thereof.

Within the field of land system science, two main approaches exist for conceptualizing spillovers. In their telecoupling framework, Liu et al. (2018, 2013) propose the notions of 'spillover systems' and 'spillover flows' as distinct units of analysis, alongside the so-called sending and receiving systems of a telecoupling flow (Figure 5a). Spillovers are thus defined in reference to a specific telecoupling flow that connects two distal socio-ecological systems. Another stream of literature uses a different starting point to define spillovers: a focal system that is linked to other systems through spillover processes (Figure 5b). In reference to land-use spillovers, Meyfroidt et al. (2020, 2018) define them as processes by which direct interventions or changes in land use in one place have impacts on land use in another place. Hence, in sum, spillovers are either defined in reference to a telecoupling connection (e.g., a commodity supply chain) or a focal system (e.g., a river basin or farm). In this study, we have investigated the governance of spillovers through VSS (Articles IV and VI). We have thereby defined and identified spillovers in reference to the farm system, as it is the primary unit of intervention of most VSS. We have thus built on the approach presented in Figure 5b.

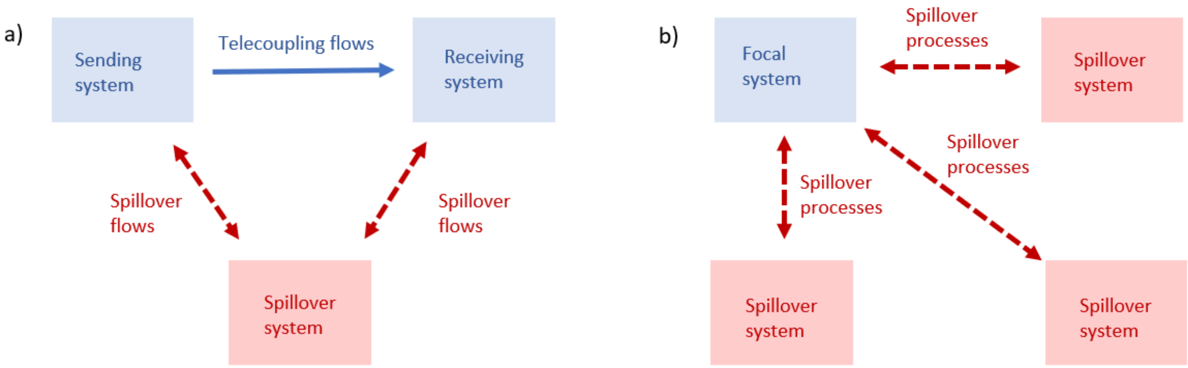

Figure 5: Different approaches to defining spillovers in land system science. a) Spillovers (in red) are defined in relation to a telecoupling process between a sending and receiving system (in blue) (based on Liu et al., 2013). b) Spillovers (in red) are defined in relation to a specific focal system (in blue) (based on Meyfroidt et al., 2018, 2020).

The concept of spillovers is commonly used to investigate whether and how specific governance interventions address externalities that take effect beyond their direct place of intervention (Dou et al., 2018; Garrett et al., 2019; Giudice et al., 2019; Heilmayr et al., 2020; Leijten et al., 2021). In their study on the effectiveness of sustainability initiatives, Garret and Pfaff (2019) distinguish between three types of spillovers: spillovers occurring across space, time and objectives. This dissertation focuses on spatial spillovers due to their relevance in the context of VSS. An important form of spillover is referred to as 'leakages' (Meyfroidt et al., 2020). Leakages are characterized by the unintended displacement of impacts caused by a governance intervention, which subsequently reduces the overall benefit of the intervention (Bastos Lima et al., 2019; Meyfroidt et al., 2018, 2013). Additionally, Bastos Lima et al. (2019) introduce the term 'boosting effects' to describe related positive dynamics that enhance the benefit of the intervention. Article VI distinguishes three types of spillovers relevant in the context of agricultural VSS. One (i.e., spillovers of VSS adoption and implementation) considers the dynamics of leakages and boosting effects. Article II furthermore identifies spillovers and leakages as key mechanisms driving boundary mismatches in the governance of telecouplings.

4. Key insights of the research articles

This chapter summarizes the main insights of the six articles presented in part II of this dissertation (see Table 1 in section 2.1 for a list of the articles and Figure 2 in section 2.2 for an overview of their contribution to the overall study objectives). A comprehensive list of references and secondary data sources is provided in the respective scientific articles.

4.1 Article I: Developing context-specific indicator frameworks for sustainability assessment of agricultural intensity change: an application for Europe

Article I investigates how changes in agricultural intensity lead to sustainability outcomes at multiple scales (contributing to objective 1). It takes a comprehensive approach to sustainable agriculture, considering spillover processes and their environmental and socio-economic effects beyond the farm level.

The article makes conceptual and analytical contributions in support of sustainability assessments of agricultural intensity change. It reveals how changes in agricultural practices affect sustainability across geographic scales and societal groups (see Figure 6). To this end, it presents the key socio-ecological processes (i.e., different types of socio-ecological flows and socio-ecological interactions, as well as ecosystem functioning processes) through which changes in agricultural intensity affect sustainability. It thereby distinguishes between several hierarchically nested scales of analysis (i.e., agricultural field, landscape, regions and the global earth system). These insights are taken up in Article IV to define spillovers and operationalize the linkages across scales that they entail.

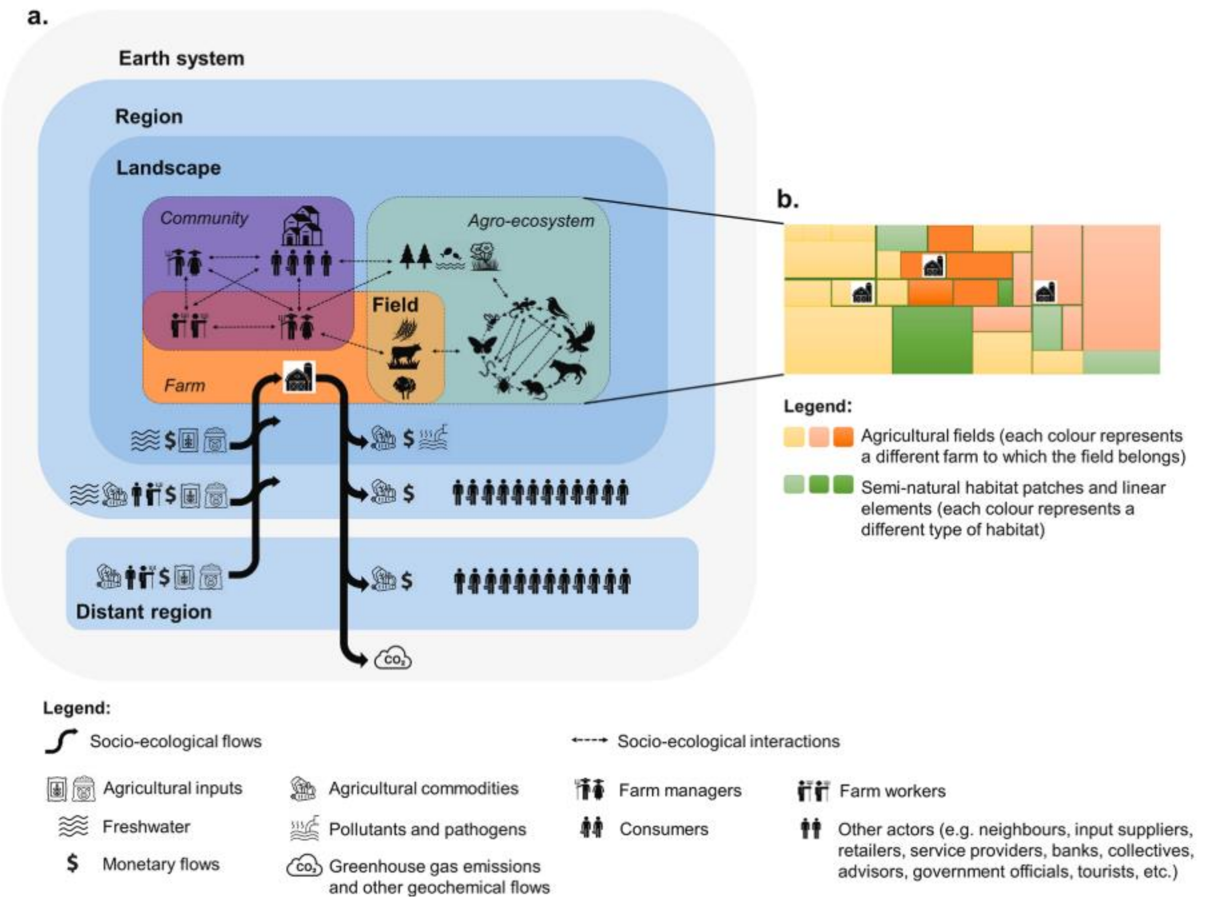

Figure 6 (reproduced from Article I): Geographical scales and organizational levels of analysis for sustainable assessment of agricultural intensity change.

The article further proposes an approach to developing context-specific frameworks for integrated sustainability assessments of agricultural intensity change. It provides a systematic rationale for identifying context-specific themes, indicators and scales of measurements for assessing the sustainability outcomes of agricultural practices. This process is based on the explicit identification and communication of relevant system boundaries, socio-ecological processes and actor groups. The proposed approach is therefore not meant as a 'one-size-fits-all' method, but rather a dynamic decision-support tool for identifying and selecting indicators in view of the overall context, scope and purpose of the analysis.

The study applies the proposed approach to the context of Europe, hence developing a multi-scale indicator framework for assessing sustainable intensification in Europe. It identifies 13 mechanisms of agricultural intensity change (e.g., input intensity change, specialization, capital intensity change, and income diversification). It further reveals processes and effects that are rarely considered in sustainability assessments. Examples include farmers' health, workers' living conditions, rural communities' cultural heritage and sense of place, impacts on sectors not directly related to agriculture (e.g., tourism), shrinking and ageing of rural population, and consumers' health.

The comprehensive, integrative and context-sensitive understanding of sustainable agriculture presented in this article is aligned with the approach taken in Articles IV and VI. Furthermore, the in-depth knowledge provided on the way (changes in) agricultural practices affect sustainability on multiple scales contributes to Article IV (and vice-versa). It helped to conceptualize and operationalize spillovers of agricultural land use. Moreover, it served the coding process conducted as part of the coverage analysis of VSS requirements, which required a detailed understanding of the linkages between agricultural practices and potential spillover effects.

4.2 Article II: Towards spatial fit in the governance of global commodity flows

Article II presents insights into the governance challenges of telecoupled agricultural commodity flows between distally connected social-ecological systems. It contributes to objective 2 of this dissertation. The article argues that the governance of telecoupled systems is beset with problems of spatial fit. It reveals important challenges regarding the design and implementation of governance institutions in terms of matching the spatial scale of the environmental and social problems generated through telecoupled commodity flows. It thereby draws on literature from the field of environmental governance, focusing on examples of global agricultural commodity flows.

The study provides novel conceptual insights regarding governance fit in telecoupled systems. It identifies two overarching types of governance mismatches: boundary mismatches and resolution mismatches (see Table 2). Boundary mismatches point to inadequate spatial extents on the part of governance interventions, where their institutional design fails to cover the full scale of the sustainability challenges targeted. Spillovers and leakages (a particular form of spillovers) are the mechanisms that drive such boundary mismatches (see section 3.2 for more information). Resolution mismatches refer to a lack of spatial precision in governance interventions, where governance institutions have too coarse a resolution to address the sustainability problems targeted.

	Boundary mismatch		Resolution mismatch
Definition†	Governance institutions neglect social-ecological problems that transcend established administrative or jurisdictional boundaries		Governance institutions have too coarse a spatial resolution to address the social-ecological problems at hand
Underlying problem	Lack of governance extent		Lack of governance precision
Mechanism	Spillover	Leakage	Panacea trap
Description	Governance institutions do not govern a social-ecological problem that expands beyond their administrative or jurisdictional boundaries	Governance institutions address a social-ecological problem but create leakage(s), i.e., counterproductive effects outside the targeted area or domain of the intervention	Governance institutions are not specific enough to be effectively implemented and enforced
Example from a public policy perspective	European countries have not (yet) implemented specific public policies to mitigate the deforestation effects of their demand for soy in remote jurisdictions	A forest moratorium shifts deforestation to neighbouring areas or other countries, producing negative externalities in distant jurisdictions	A Multilateral Environmental Agreement that is too broad in scope to govern particular telecoupled flows
Example from a private governance perspective	A Voluntary Sustainability Standard focuses on reducing harmful on-farm impacts at sites of production but neglects sustainability issues outside the farm such as air pollution from pesticide use	Supply chain actors implement zero-deforestation policies that target only one region, allowing actors in other regions or neighbouring countries to deforest	Supply chain actors set broad sustainability goals that are insufficiently operationalized and lack specific and measurable targets, unambiguous definitions and exact coverage

†Adapted from Bergsten et al. (2014)

Table 2 (reproduced from Article II): Boundary and resolution mismatches in the governance of telecoupled socio-ecological systems.

The article reveals that telecoupling-related governance mismatches can be addressed through governance (re)scaling. This involves scaling up existing governance institutions (e.g., expanding their area of intervention, target groups or supply chain scope) or scaling them down (e.g., enhancing the context sensitivity of and stakeholder participation in interventions). Furthermore, new governance scales can be created to address mismatches (see e.g., due diligence laws). The article provides three illustrative examples of governance rescaling approaches in public and private governance interventions: trade agreements, due diligence laws and landscape approaches to supply chain governance. It thereby presents opportunities and challenges involved in addressing boundary and resolution mismatches.

The article acknowledges that, in telecoupled contexts, no single governance approach is likely to address all mismatches. Furthermore, finding an ‘optimal spatial scale’ may not be possible. The article thus stresses the need to align multiple governance interventions for effective governance of telecoupled systems. It calls for more research on the interplay between different governance institutions targeting certain telecoupling phenomena (e.g., through social-ecological network approaches) in order to inform the design of governance systems in which effective institutional interplay offsets spatial mismatches of single institutions.

The empirical part of the dissertation draws and builds on the conceptual insights presented in this article. For Articles IV and VI, we investigated boundary mismatches for the case of voluntary sustainability standards (see private governance example for spillovers and boundary mismatches in Table 2). We particularly focused on the spillover mechanisms driving such mismatches as well as potential rescaling approaches for addressing them (e.g., landscape approaches).

4.3 Article III: Why telecoupling research needs to account for environmental justice

This debate paper emphasizes the importance of integrating insights from environmental justice scholarship into telecoupling research and the governance of telecoupling phenomena. It argues that (in)justices are often fundamental features of telecoupling dynamics, as social-ecological flows across distances often create winners and losers. The article identifies suitable approaches for incorporating environmental justice perspectives into telecoupling research, structured along the three dimensions of environmental justices: distributive justice, procedural justice and recognitional justice (Schlosberg, 2007).

The article identifies important justice-related elements to consider when governing and researching telecoupling phenomena (contributing to objective 2). First, it calls for the increased recognition and consideration of benefits and burdens generated by telecouplings across distances. This argument is taken up in Articles I and VI, where we discuss governance practices regarding the distant implications of sustainable agriculture. Second, it points to issues regarding procedural justice and power in the governance of telecoupled systems. It calls for balanced and fair stakeholder representations in decision-making procedures in telecoupling contexts, thereby highlighting the importance of identifying and involving affected people, who may be distantly located. Furthermore, it points to the importance of paying attention to power dynamics. Article I builds on this, highlighting the importance of considering power asymmetries in participatory sustainability assessments regarding agricultural practices and their (telecoupled) outcomes. In Article VI, we further discuss these topics in relation to stakeholder representation procedures in VSS. Third, the paper argues that we should reflect on telecoupled information flows, including the values and interests in which they are embedded – both visible and invisible. Finally, the paper further highlights key mechanisms for addressing injustices in telecoupled land systems, e.g., through transparency initiatives, state governance regulations or transnational activism.

4.4 Article IV: Governing spillovers of agricultural land use through voluntary sustainability standards: a coverage analysis of sustainability requirements.

Article IV adopts a telecoupling perspective to assess the governance of agricultural land use through voluntary sustainability standards (contributing to objectives 1 and 2). It thereby focuses on spillovers of agricultural land use, defining them as socio-economic or environmental processes that are triggered by agricultural land use and affect sustainability in near or distant places outside the farm (see section 3.2 and the article for more conceptual elaborations).

The article shows that in a telecoupled world, a comprehensive and integrative notion of sustainable agricultural land use requires explicit consideration of the processes that link agricultural practices with impacts beyond the farm in near and distant places, i.e., spillovers of agricultural land use. Applying a land system science perspective, the article adopts a comprehensive approach in order to define and identify a wide range of social-economic and environmental spillovers of agricultural land use. It draws on insights from a multitude of disciplines to operationalize the concept further, presenting an elaborate, though non-exhaustive, set of 21 social-economic and environmental spillovers of agricultural crop production.

The article argues that, in view of a more comprehensive notion of sustainable agriculture, spatial scale mismatches are a key design challenge of VSS (i.e., indicating that their scale of intervention is incongruent with the scale at which the sustainability challenges that they are targeting occur). The article investigates the extent and nature of such mismatches by analysing the content of 100 sustainability standards in order to assess the extent to which they regulate spillovers of agricultural land use. The article reveals that spillovers are, at least implicitly, present in many standards' requirements. This implies that VSS can make contributions towards sustainability beyond the farm level through the consideration of spillovers in their standard requirements. However, the extent to which they do so in practice differs largely among different types of spillovers (see Figure 7). Moreover, the study reveals considerable regulatory gaps. Socio-economic spillovers, in particular, are less extensively regulated through VSS than environmental spillovers. While VSS tend to regulate management practices that have environmental implications beyond the farm level, they tend to focus on VSS requirements that target socio-economic outcomes within the farm only. Individual VSS further show a tendency towards a similar degree of (implicit) ambition to regulate both environmental and socio-economic spillovers. Hence, if they have a high coverage of environmental spillovers, they also tend to regulate socio-economic spillovers more extensively, albeit to a lower overall extent. Finally, the article points to variations in the way different types of VSS systems address (certain) spillovers. For example, public VSS appear to have a lower spillover coverage than company-based or other private VSS.

The article critically discusses these results in terms of the potential role that VSS can have in fostering sustainability of agriculture in a telecoupled context. Pointing to important VSS implementation challenges, the article clarifies that the analysis of VSS requirements indicates the aspired change by VSS, but not their actual impact on the ground. Hence, the results do not point to the performance of individual standards, but rather present a sector-wide overview of priorities and potential gaps in the coverage of spillovers in VSS. Furthermore, the article argues that simply broadening the thematic coverage of standards to address a broader range of spillovers does not necessarily lead to better VSS performance and may not be in line with the standards' scope of objectives. It highlights that, in a telecoupled world, spillovers are omni-present and hence it is impossible for VSS (or any other governance instrument) to govern them all. The article thus recommends that standard-setting organizations should systematically identify spillovers with a large potential for supporting or undermining their sustainability objectives and focus their efforts on the most relevant ones (considering their sustainability implications and the standards' feasibility of regulating them). Finally, the article sheds light on and discusses the role of scientific knowledge in governing spillovers through VSS. It emphasizes the need for sustainability research to encompass a wide range of spillovers, enabling an informed and engaged dialogue among science, policy, and society. This dialogue is crucial for advancing effective governance of sustainable agriculture across different scales.

The article contributes to this dissertation by providing empirical insights into the extent of spatial scale mismatches in the case of a governance instrument that is prominently used to foster sustainable agriculture: voluntary sustainability standards. It applies and further develops the conceptual knowledge gained from the synthesis research conducted in the frame of this dissertation on sustainable agriculture (Article I) and scale mismatches (Article II) in telecoupling contexts. It further lays the base for Article VI, where we explore different avenues for integrating telecoupling perspectives in VSS systems.

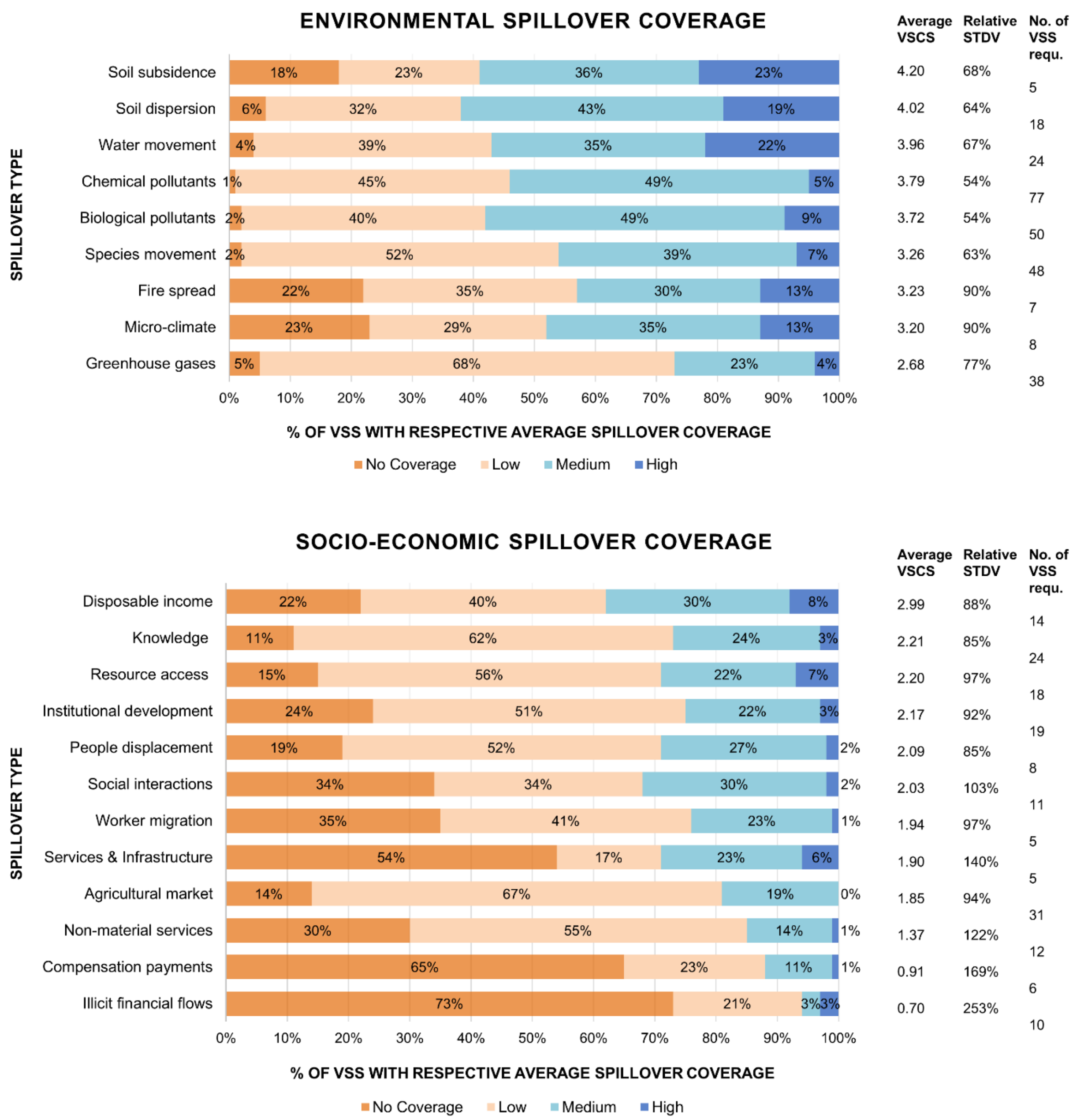

Figure 7 (reproduced from Article IV): Relative share of VSS with different levels of spillover coverage, by spillover type.

4.5 Article V: Telecoupling visualizations through a network lens: a systematic review

Article V provides insights into the way visualizations are and can be used for effective communication of knowledge about telecoupling phenomena (contributing to objective 3). It argues that visualizations are powerful communication tools for co-producing, depicting, analysing and communicating scientific knowledge, particularly in the case of abstract and intangible subjects – which telecoupling phenomena often are. It shows that they are commonly and diversely used by telecoupling researchers to illustrate how socio-ecological systems are connected across distances.

The article presents a systematic review of existing telecoupling visualization practices, taking stock of their content, as well as existing techniques to visualize telecoupled land system dynamics. It applies a network-based approach in order to investigate a highly diverse set of 118 telecoupling visualizations in a unified manner, analysing them in terms of their node-link structure (i.e., the key components of networks). Through this approach, the article demonstrates the ubiquity and importance of network perspectives in telecoupling visualizations and research. Drawing on insights from social network science, it further identifies alternatives for conceptualizing links in telecoupling (i.e., as interactions, relations or similarities, rather than flows only).

Regarding telecoupling visualization content, the article reveals that existing telecoupling visualizations typically present networks of social-ecological systems, which are linked through flows (as in the telecoupling framework proposed by Liu et al. (2013)). Displays of telecoupling connections through actor networks or action situation networks also exist but are less frequent. The article further shows that telecoupled systems are most commonly displayed through territorial governance units and that they are often defined at a high level of aggregation (e.g., through nation states). In the context of these findings, the article argues that visualizations are often representations of the researchers' mental models of the investigated phenomena. It suggests that the visualization process can provide opportunities for researchers to reflect critically on their underlying assumptions and perspectives (e.g., regarding the boundaries used to define telecoupled systems) and to communicate them transparently through visuals.

In view of the visualization techniques used, the article identifies seven types of telecoupling visualizations. They differ in terms of the visual encoding strategies used to represent key telecoupling components. The most used visualization types are *relational graphs* (e.g., schematic diagrams, network diagrams or chord diagrams) and *quantity graphs* (e.g., bar charts or line graphs), while spatially explicit types are less common (e.g., *link maps* or *quantity maps*). The article also provides insights into the relative frequency of the use of the different visualization types for different telecoupling topics (e.g., commodity trade, species migration or tourism).

The article points to potential biases that visualizations can introduce. It shows that the design of effective and accessible visualizations is particularly challenging in telecoupling research due to the diversity of subjects, analytical approaches and richness of data involved. It identifies a key challenge for visualizing telecouplings: the integration of multiple perspectives into visuals without overloading the visualization or oversimplifying the subject matter (Kirk, 2016; Munzner, 2014). The article thus calls for a careful and critical selection of visualization content and design that adequately and purposefully represents telecoupling phenomena. The article provides practical recommendations for visually communicating information about telecoupling phenomena in an accessible way. For example, it presents good practice examples, strategies for combining multiple perspectives in graphs, and information about helpful tools. It also identifies thus far unused data visualization techniques, which present alternative ways to visualize telecouplings.

The insights gained from this article on visualization content, techniques and potential pitfalls were used in Articles I, II, IV and VI, where we designed and used visuals to communicate and explain telecoupling phenomena. They were particularly valuable for Article VI, where we used visualizations to explain the concepts of 'telecoupling' and 'spillovers' during interviews with non-scientific experts.

4.6 Article VI: Fostering sustainable agriculture beyond the farm level: entry points and barriers for voluntary sustainability standards

Article VI investigates the different strategies that standard-setting organizations can use to integrate spillover perspectives into their standard systems. It presents insights into the way telecoupling phenomena can be governed and communicated, contributing to objectives 2 and 3.

The article builds on the findings from Article IV, which indicates considerable gaps regarding the regulation of spillovers of agricultural land use through the requirements presented in the standard documents and at the same time also points to limitations on simply expanding the scope of VSS documents. This article reveals potential ways to increase VSS systems' consideration of telecoupling perspectives. It identifies and critically discusses a range of potential strategies by which standard-setting organizations can integrate spillover perspectives in standard systems (thus going beyond the standard document). To do so, it draws on insights from key informant interviews with VSS experts, results from an analysis of data on VSS system characteristics for 69 agricultural standards, and inputs from scientific and grey literature.

The article builds on and further develops the conceptual contributions on spillovers presented in Article IV. It identifies three types of spillovers related to agricultural VSS: 1) agricultural land use spillovers; 2) supply chain spillovers; and 3) VSS adoption and implementation spillovers. The three types served to clarify and communicate the spillover concept during our interactions with non-scientific VSS experts. While Articles I and IV focus on agricultural land use spillovers only, this article considers all three spillover types in its analysis.

The article presents several entry points and barriers for integrating spillover perspectives (Figure 8). They are situated within five different domains of sustainability standard systems. At a strategic level, the objectives and design of VSS systems set the overall direction and frame for the standards' role in governing spillovers. Strategic decisions regarding standards' Theory of Change and their scale of intervention can thus largely shape the potential for VSS systems to foster sustainability beyond scale. Standard-setting procedures are critical for identifying potentially relevant spillovers and setting priorities regarding the integration of spillover-relevant contents in VSS requirements. Inclusive stakeholder consultations and balanced decision-making processes play an important role therein. Furthermore, VSS implementation mechanisms can be used to unravel (unregulated) sustainability risks and thereby inform standard-setting. VSS regulate spillovers directly or indirectly through the requirements stipulated in their standard documents. This article reveals that they do so most commonly through provisions regarding on-farm practices that can trigger spillover processes rather than through regulation of spillovers themselves or their impacts. Finally, it shows that the non-certification-based activities of standard-setting organizations (e.g., landscape initiatives) also provide opportunities to identify and address potential spillovers.

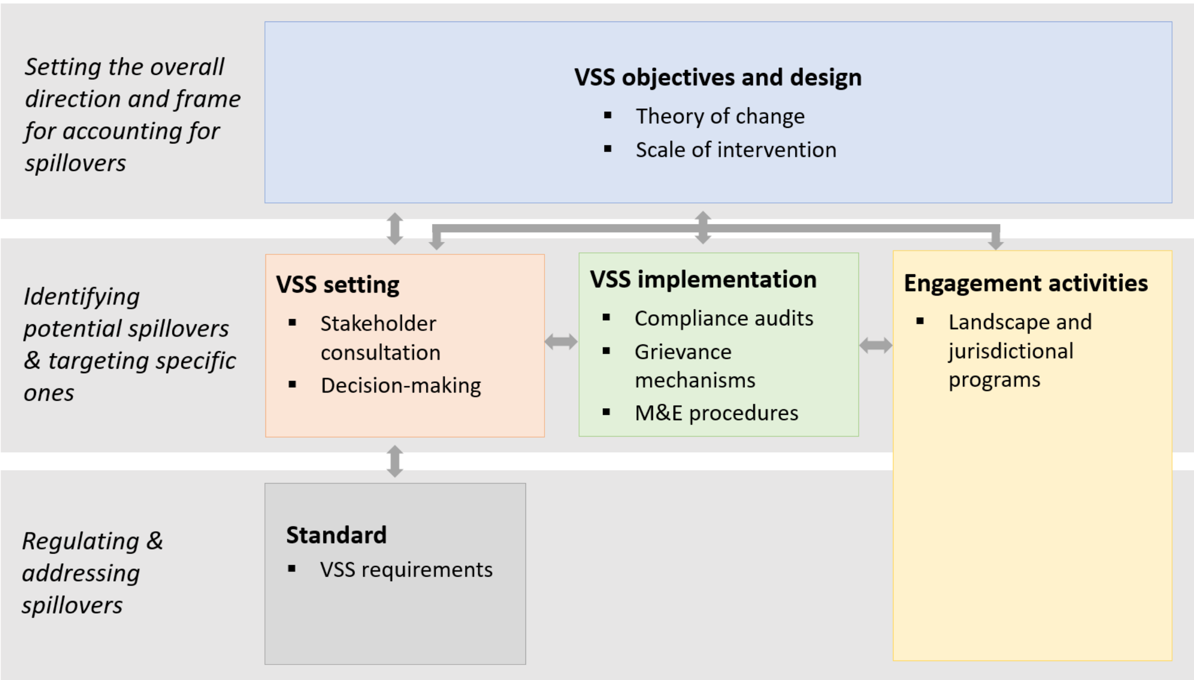

Figure 8 (reproduced from Article VI): Entry points for integrating spillover perspectives in five domains of the VSS system.

The article thus reveals much potential for VSS systems to foster sustainability beyond farm level. However, it also demonstrates that this potential is underused in current practice and points to existing barriers to adopting and implementing the presented entry points. For instance, a tendency towards theme-centred priority setting in VSS systems (Manning and Reinecke, 2016) hampers a more systematic and explicit consideration of spillovers when defining the objectives and contents of standards. Furthermore, the existing practices of unbalanced stakeholder consultation inputs and decision-making procedures in VSS setting (see e.g., Ponte and Cheyns, 2013; van der Ven, 2022) can hamper the uptake of spillovers. The article concludes that standards are not equally suitable for addressing all types of spillovers. It thus calls for continuous, explicit discourses about the existence, relevance and governability of spillovers in VSS systems. Furthermore, it indicates that spillovers cannot be addressed through standards alone, pointing to the complementary role of non-certification-based activities within and beyond VSS systems.

The methodological approach used for this article also provides insights into the communication of telecoupling knowledge to a non-scientific public (see objective 3). Visualizations were used during the interviews as tools to communicate the telecoupling and spillover concepts to the respondents. This practice proved helpful in making these to-date unfamiliar concepts more accessible and tangible to the VSS experts (as also suggested in the data visualization literature; see e.g., McInerny et al., 2014). The adopted research methods show that visuals can provide a useful means to structure and guide interviews and to stimulate the active participation of experts in the knowledge creation process.

5. Synthesis and outlook

In this study, I set out to foster scientific understanding of the sustainable agriculture in a telecoupling context, as well as the governance and communication of telecoupling phenomena. It thereby placed a focus on spillovers of agricultural land use and their governance through voluntary sustainability standards, as well as on visuals as a means to communicate telecoupling knowledge. This chapter synthesizes the main insights from the study and presents avenues for further research. It is structured along the themes of the three main objectives presented for this dissertation (see section 1.3).

Telecoupling and sustainable agriculture

This dissertation underlines the need for a comprehensive and integrative understanding of sustainable agriculture in today's telecoupled world, wherein explicit consideration must be given to spillover processes. It addresses existing knowledge gaps regarding the conceptualization and operationalization of spillovers of agricultural land use. Building on the existing literature on spillovers (Meyfroidt et al., 2020, 2018), it defines them as processes that are triggered by agricultural land use and affect sustainability in near or distant places outside the farm. It thereby takes a comprehensive approach that encompasses a wide range of socio-economic and environmental processes.

The dissertation shows that spillovers can significantly reinforce or undermine ongoing sustainability efforts. Therefore, it emphasizes the necessity for a more explicit discourse about telecoupling dynamics and spillovers in particular, given that sustainable agriculture is defined and operationalized for the design and evaluation of governance instruments that claim to foster sustainable agriculture. This dissertation offers knowledge and practical tools that could aid researchers and policymakers in this endeavour. It presents a comprehensive, although not exhaustive, compilation of socio-economic and environmental spillovers associated with agricultural land use. It also proposes an inclusive analytical framework to assess the sustainability outcomes resulting from changes in agricultural practices across multiple scales, considering the unique context of each situation. These advancements serve as initial steps in addressing spillovers more explicitly in research and policymaking. However, there is a need for additional knowledge and tools to deepen our understanding of how sustainable agriculture can be effectively assessed in a telecoupled world. This includes the development of enhanced methodologies and frameworks to identify and measure spillovers, evaluate their sustainability impacts, and prioritize them accordingly.

Telecoupling and sustainability governance

This dissertation explores the role of Voluntary Sustainability Standards (VSS) in effectively governing telecoupling phenomena associated with agricultural production. Specifically, it focuses on investigating a significant challenge in VSS design, namely spatial scale mismatches, and examines spillovers as the key mechanisms underlying these challenges. The study identifies two types of scale mismatches—boundary mismatches and resolution mismatches—that pose significant challenges to the effective governance of telecoupling phenomena (Article II). The research findings indicate that boundary mismatches are a prevalent design challenge for VSS systems. While sustainability standards aim to promote sustainable agricultural production, their implementation primarily occurs at the farm level. However, to achieve a comprehensive and integrated approach to sustainable agriculture that considers telecoupling dynamics, VSS must also address spillovers that result in impacts beyond the farm level.

The dissertation presents several strategies that standard-setting organizations can employ to address this design challenge. It identifies current practices, as well as distinct strategies for better integrating spillover perspectives into VSS (Articles IV and VI). These strategies revolve around three main lines of intervention. First, standard-setting organizations can explore *opportunities within their existing VSS design* and related certification activities. The most straightforward approach involves progressively targeting spillovers through the requirements specified in the standard documents, which certified members must adhere to. Our empirical analysis of 100 agricultural VSS reveals that standards already regulate spillovers through their requirements. However, there are regulatory gaps, particularly in addressing socio-economic spillovers, which receive less attention than environmental spillovers. To improve this practice, interviews with VSS experts suggest different operational-level mechanisms to aid in identifying and prioritizing spillovers in standard-setting. Additionally, explicit discourse and consideration of spillovers in strategic priority setting are crucial. Second, standard-setting organizations can *modify the VSS design* by rescaling their certification activities. This could involve establishing certification of whole landscapes or jurisdictions. Currently, this approach is less prevalent in practice, although initial efforts are underway. Consequently, further research is necessary to evaluate its effectiveness and determine its potential benefits. Third, standard-setting organizations can *broaden their portfolio beyond certification activities*, for instance, through engaging in landscape-level programs. This approach has gained traction and offers the opportunity to address some of the inherent scale mismatches associated with farm-level certification. However, it requires structural changes within standard-setting organizations as they diversify their activities. It also has limitations in terms of spatial scope, as a telecoupling perspective highlights spillovers that extend beyond the landscape level.

The dissertation highlights several significant barriers to the implementation of the strategies uncovered for integrating spillover perspectives in VSS systems. It is crucial to recognize that sustainability standards often present substantial challenges in their design and implementation that go beyond spatial scale mismatches. Their effectiveness is frequently subject to scrutiny, raising doubts about their ability to fully achieve desired sustainability outcomes (see e.g., DeFries et al., 2017; Dietz and Grabs, 2022; Oya et al., 2018; Traldi, 2021). Simply expanding the coverage of standards to address numerous spillovers can, therefore, be challenging and potentially counter-productive. It is essential to ensure that by increasing the focus on spillovers, existing challenges are not further exacerbated and that less powerful and resourceful actors are adequately protected. Furthermore, in an interconnected world, potential spillovers can manifest in various forms and contexts, making them pervasive. Therefore, the goal should not be to indiscriminately govern all spillovers, but rather to systematically reflect on their existence, relevance, and governability, and prioritize accordingly.

Therefore, although VSS can play a significant role in promoting sustainable agriculture beyond the farm level, they may not always be the most suitable instrument for governing all types of spillovers, and they cannot address spillovers alone. This emphasizes the necessity for further research on the role of other governance instruments, such as due diligence regulations and company policies, in effectively governing telecoupling phenomena. Furthermore, it underscores the importance of achieving a better understanding the complementary roles that different governance instruments can fulfill in jointly fostering sustainable agriculture across multiple scales.

Telecoupling and science communication

This dissertation highlights the significance of an engaged dialogue between academia and practitioners in promoting effective governance of sustainable agriculture beyond scale. The empirical evidence on the coverage of spillover dynamics through VSS indicates that the presence (or absence) of scientific knowledge in telecoupling dynamics can play an important role in its uptake in governance instruments (Article IV). The dissertation identifies challenges relating to the lack of a harmonized understanding of relevant concepts and methodological issues in identifying and measuring different types of spillovers. It emphasizes the essential role of effective knowledge communication at the science-policy-society interface, particularly when dealing with telecoupling phenomena that are usually multi-scalar and encompass various thematic perspectives.

The dissertation examines the current practices and challenges associated with the communication of scientific knowledge on telecoupling and presents recommendations for improvement. It thereby focuses on visualizations, as they are powerful tools for making complex and intangible topics accessible to a broad audience (McInerny et al., 2014). Visuals are widely and diversely used by the telecoupling research community to share its scientific findings. The methodological approach employed in Article VI, involving visual elicitation methods during key informant interviews, demonstrates the value of visuals as tools for communicating the concepts of ‘telecoupling’ and ‘spillovers’ to non-scientific audiences. This further helped to stimulate engaging discussions on the opportunities and challenges of governing telecoupling phenomena.

These findings emphasize the significant potential of using visuals in co-creating and communicating knowledge on telecouplings. However, the design of such visuals raises important questions: What content should they include and exclude? How can telecoupling phenomena be represented without overloading the visual or oversimplifying the content? The dissertation provides insights that can guide the process of designing effective and purposeful telecoupling visualizations (Article V). It offers an overview of different approaches and techniques used for visual representation of telecoupling dynamics. Additionally, it highlights key challenges and potential biases in visualizing telecouplings, while providing practical insights on improving current practices. Lastly, the dissertation emphasizes the importance of exploring alternative tools for the communication and co-production of telecoupling knowledge, to create more inclusive and effective science-policy dialogues that can address the complex challenges of sustainable agriculture in a telecoupled world.

6. Research contributions

Drawing on all six research articles, this chapter highlights the scientific and societal contributions made by this dissertation.

6.1 Scientific contributions

This dissertation makes multifaceted contributions to both telecoupling research and land system science, spanning across conceptual, empirical and methodological domains.

Conceptual contributions

The dissertation uncovers novel insights regarding the two core concepts it uses: telecoupling and spillovers (see chapter 3).

In the realm of telecoupling governance, this study makes several conceptual contributions. It introduces two overarching categories of governance mismatches and proposes rescaling approaches as potential remedies (Article II). Furthermore, it sheds light on the pivotal role of environmental justice (Article III) and illuminates the significance of network perspectives within telecoupling research (Article V). By drawing upon social network analysis, it expands the conceptualization of telecoupling connections outside the commonly-used focus on flows (Liu et al., 2013; Munroe et al., 2019).

The dissertation advances the conceptual understanding of 'spillovers' in the context of agricultural land use and commodity flows by offering insights into further operationalization and concrete applications of the concept. It presents a comprehensive framework that enables the analysis of spillovers in the context of agricultural VSS, drawing upon insights from various scientific disciplines. It further identifies three distinct types of spillovers in the context of agricultural VSS (Article VI) and provides an extensive inventory of 21 socio-economic and environmental spillovers associated with agricultural land use (Article IV). The study builds and expands upon previous conceptualizations of land use spillovers (in particular, presenting insights on what Meyfroidt et al. (2020) categorized as 'other spillovers'). Furthermore, the dissertation introduces a systemic approach to developing comprehensive indicator frameworks for integrated sustainability assessments of agricultural changes, encompassing interactions and outcomes at multiple scales (Article I). The combined insights into spillovers of agricultural land use could extend beyond the realm of VSS governance and contribute to the broader governance of agricultural land use. They lay the foundation for further analyses that would employ telecoupling perspectives to examine sustainable agriculture holistically or to explore the coverage of spillovers within alternative supply chain initiatives and governance instruments (e.g., mandatory laws or corporate sustainability targets).

Empirical contributions

The dissertation effectively combines the topics of 'spillovers' and 'sustainability standards,' which have gained considerable scientific attention in recent years (Articles IV and VI). It responds to the growing demand for further research on spillovers in agricultural land use (Meyfroidt et al., 2022), their governance (Liu et al., 2018; Meyfroidt et al., 2020), and the design of VSS (Marx et al., 2022). By integrating these research areas and employing empirical methods, the dissertation addresses critical research gaps. It provides a comprehensive assessment of the extent to which socio-economic and environmental spillovers are targeted in governance instruments, focusing specifically on the case of VSS. Additionally, it offers insights into potential strategies for transforming VSS systems to more effectively address spillovers.

Moreover, this dissertation presents novel empirical evidence on the utilization and design of telecoupling visualizations, which play a crucial role in facilitating the communication of telecoupling knowledge within the science-policy-society nexus (Article V). While the research community has shown limited attention to the role of visualizations in telecoupling studies thus far, there has been substantial reliance on visuals for effective communication. By shedding light on the current practice of telecoupling visualizations and offering recommendations for improvement, this dissertation addresses important knowledge gaps in the field.

Methodological contributions

This dissertation makes three significant methodological contributions.

First, it applies an innovative approach for systematically examining visualizations featured in scientific literature (Article V). It builds upon established methods that involve systematic reviews of extensive scientific texts (see e.g., Cooper, 2019; Petticrew and Roberts, 2006) and detailed content analyses of visuals (Van Leeuwen and Jewitt, 2001). The distinguishing feature of this study lies in the systematic analysis of a large number of visuals. This was made possible through the identification and combined analysis of the basic components of telecoupling phenomena (i.e., nodes and links) and visualizations (i.e., marks and attributes). Through this unique methodological approach, different types of telecoupling visualizations could be uncovered.

Second, it undertakes a comprehensive assessment of the contents of standard documents, using an extensive sample of standards (Article IV). It differs from previous studies that have primarily concentrated on specific commodity sectors (e.g., Dietz et al., 2018; McInnes, 2017; Schleicher et al., 2019) or targeted particular sustainability topics (e.g., biodiversity (Potts et al., 2017; Tayleur et al., 2017), thereby often relying on smaller sample sizes (see e.g., Elder et al., 2021; IISD, 2019; Potts et al., 2014). In this regard, an elaborate approach was employed, involving meticulous selection, coding, aggregation and analysis of data from the ITC Standards Map database, showcasing its potential for examining VSS contents across various thematic focuses.

The third methodological contribution originates in the application of visual elicitation methods during the interviews (see Article VI). While an increasing body of literature highlights the advantages associated with using visuals during interviews (see e.g., Bravington and King, 2018; Glegg, 2019; Orr et al., 2020), its utilization remains relatively uncommon in the field of land system science. This approach proved especially advantageous for gathering data pertaining to telecoupling phenomena, given the inherent abstraction associated with the telecoupling framework.

6.2 Societal contributions

This dissertation provides knowledge that could improve the governance of spillovers in the context of sustainable agriculture. This is key, as spillovers can have substantial sustainability implications beyond the farm level, potentially undermining efforts to promote more sustainable agricultural practices and supply chains. This research highlights the presence and relevance of spillover perspectives in defining sustainable agriculture and presents knowledge for improving existing governance efforts in this regard. It thereby focuses on one of the most widely used instruments for governing agricultural supply chains: Voluntary Sustainability Standards.

The dissertation contributes to currently ongoing developments in the VSS practitioners' community, as standard-setting organizations are increasingly striving to achieve impact beyond farm and supply chain levels. They do this, for instance, by adjusting the requirements for sustainable agricultural practice in their VSS documents and initiating or engaging in initiatives at landscape or jurisdictional level. Our dissertation supports them in this process in four main ways:

- First, by identifying and presenting a comprehensive set of potentially relevant spillovers of agricultural land use, the dissertation offers insights into the multi-scalar outcomes of agricultural activities. This knowledge could assist standard-setting organizations in the process of defining their Theory of Change and the content of their standards.

- Second, the dissertation provides insights into the current practices of standard-setting organizations in addressing spillover dynamics. This knowledge offers an opportunity to identify and reflect on elements that may not yet be adequately covered by existing standards but are relevant to the effective governance of agricultural supply chains. This information could be valuable for standard-setting organizations as they strive to enhance their practices and improve sustainability outcomes.
- Third, the dissertation does cover the potential use of landscape and jurisdictional initiatives to support standards-setting organizations in their quest, but also highlights the need to look beyond landscape and jurisdictional levels when considering the governance of spillovers. By pointing out this need, the dissertation encourages standard-setting organizations and policymakers to apply a telecoupling perspective to explore innovative approaches that consider the wider, multi-scalar implications of their actions.
- Fourth, during the study, I initiated and engaged in discussions with VSS experts and standard-setting organizations on the way VSS systems can be transformed for effective addressing of spillover dynamics. This contributed to a productive science-practitioners dialogue, fostering transdisciplinary collaboration and knowledge exchange. Such a dialogue is crucial for enhancing the governance of telecoupled phenomena in agriculture.

Lastly, this dissertation could play an active role in promoting effective communication on telecoupling phenomena at the science-policy-society interface. Policymakers are facing growing societal concerns relating to sustainability in a telecoupled world, e.g., regarding the far-reaching implications of land use and the products consumed. In this context, effective communication and the establishment of a shared understanding of telecoupled processes are key. This dissertation contributes to these ongoing developments by highlighting the potential of visualizations as a means to share knowledge on telecoupling and by providing practical recommendations to enhance current practices.

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PART II:

RESEARCH ARTICLES

Article I: Developing context-specific indicator frameworks for sustainability assessment of agricultural intensity change: an application for Europe[1]

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Developing context-specific frameworks for integrated sustainability assessment of agricultural intensity change: An application for Europe

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A R T I C L E I N F O

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A B S T R A C T

Agriculture plays a central role in achieving most Sustainable Development Goals (SDGs). Sustainable intensification (SI) of agriculture has been proposed as a promising concept for safeguarding global food security, while simultaneously protecting the environment and promoting good quality of life. However, SI often leads to context-specific sustainability trade-offs. Operationalising SI thus needs to be supported by transparent sustainability assessments. In this article, we propose a general systematic approach to developing context-specific frameworks for integrated sustainability assessment of agricultural intensity change. Firstly, we specify a comprehensive system representation for analysing how changes in agricultural intensity lead to a multitude of sustainability outcomes affecting different societal groups across geographical scales. We then introduce a procedure for identifying the attributes that are relevant for assessment within particular contexts, and respective indicator metrics. Finally, we illustrate the proposed approach by developing an assessment framework for evaluating a wide range of intensification pathways in Europe. The application of the approach revealed processes and effects that are relevant for the European context but are rarely considered in SI assessments. These include farmers' health, workers' living conditions, cultural heritage and sense of place of rural communities, animal welfare, impacts on sectors not directly related to agriculture (e.g., tourism), shrinking and ageing of rural population and consumers' health. The proposed approach addresses important gaps in SI assessments, and thus represents an important step forward in defining transparent procedures for sustainability assessments that can stimulate an informed debate about the operationalisation of SI and its contribution towards achieving SDGs.

1. Introduction

Agriculture is pivotal for achieving most of United Nations Sustainable Development Goals (SDG) targets (Ehrensperger et al., 2019; FAO, 2018). This interconnectedness means that complex interactions may emerge among different development priorities, possibly leading to synergies, but also to competing demands (Kroll et al., 2019; Pham-Truffert et al., 2020). Coherent solutions are therefore required to enable sustainability transformations in agriculture capable of fostering SDG co-benefits and navigating their potential trade-offs (Caron et al., 2018).

A large number of approaches for sustainable agricultural production have emerged in recent decades, proposing diverse pathways to

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reconcile the requirements for safeguarding global food security with preserving the environment and promoting good quality of life (Oberč and Schnell, 2020). The concept of sustainable intensification (SI) proposes three underlying principles to tackle these challenges: i) increasing agricultural productivity; ii) improving resource-use efficiency and reducing the use of harmful inputs; and iii) halting expansion in important biodiversity hotspots by confining food production to existing farmland (Godfray et al., 2010). SI originally revolved around identifying and promoting farming practices allowing for productivity gains while keeping adverse environmental impacts at a minimum (Pretty, 1997). Such alleged win-wins have subsequently been widely endorsed by scientists, governments and international organisations, particularly in the context of smallholder farming in developing countries (FAO, 2011; Pretty et al., 2011). However, the concept of SI has been increasingly criticised for being too weakly and narrowly defined to merit the term "sustainable", leading to calls for extending its scope beyond productivity and environmental objectives (Cook et al., 2015; Loos et al., 2014; Struik and Kuyper, 2017). Current perspectives emphasise that SI needs to equally engage with the social and economic dimensions of sustainability, and be fully embedded within the multiple dimensions of food systems (Rockström et al., 2017; Struik and Kuyper, 2017). This implies that intensification impacts on biodiversity, climate change and food availability must be considered along with a range of sustainability outcomes on rural livelihoods and social cohesion (Helfenstein et al., 2020).

Different societal groups often have disparate preferences in terms of which outcomes should be prioritised or avoided (Bennett et al., 2021; Pérez-Soba et al., 2018). Given that sustainability outcomes are not independent of each other, agricultural intensification will almost inevitably lead to trade-offs and to different sets of winners and losers (Egli et al., 2018; Kanter et al., 2018). Hence, SI requires the development of a shared system of values and norms (Struik et al., 2014). The operationalisation of SI should thus not be simply regarded as the adoption of a set of prescribed farming practices, but instead as a process of social negotiation, institutional innovation and adaptive management (Schut et al., 2016; Struik et al., 2014). In this sense, SI can be interpreted as a "boundary object" (*sensu* Franks, 2014) or a guiding principle (Smith, 2013), about which stakeholders can negotiate problems and conflicts, to iteratively and incrementally arrive at solutions drawing on the full range of SI approaches. Such a process should ideally be informed and supported by a comprehensive and transparent trade-off assessment of alternative SI pathways (Helfenstein et al., 2020; Struik and Kuyper, 2017).

Assessing the extent to which changes in agricultural intensity affect sustainabiliy outcomes is, however, highly challenging (Struik et al., 2014). It involves appraising and anticipating several indirect and long-term effects beyond the farm level, including environmental spill-overs and cascading effects on ecosystems and biogeochemical cycles (Campbell et al., 2017; Tilman et al., 2002; Vignieri, 2019), changes in social relationships and norms (Janker et al., 2019), and market-related dynamics (García et al., 2020). Moreover, such processes and outcomes are highly context-specific, depending to a large extent on the historical developments, socio-economic conditions and institutional settings in which they are embedded (Tappeiner et al., 2020). Finally, conflicting sustainability outcomes may co-emerge at different geographical scales. For example, land-use redistribution (Rising and Devineni, 2020) and optimisation through international trade could in principle contribute to lower global greenhouse gas (GHG) emissions and food prices (Popp et al., 2017), but also lead potentially to irreversible localised impacts on sensitive ecosystems, rural livelihoods and indigenous communities (Lambin, 2012). Hence, changes in agricultural intensity and resulting trade-offs must be evaluated across different normative dimensions, geographical scales and contexts (Helfenstein et al., 2020; Kanter et al., 2018; Thomson et al., 2019).

Different assessment frameworks and tools have been proposed in recent years for evaluating the sustainability of alternative agricultural development trajectories. Sustainability assessment tools at the field/farm level, for example, can quantify in detail the impacts directly triggered by the practices and use of resources within those management units. However, they fail to fully account for the dynamic interactions with surrounding ecosystems and communities (Eichler Inwood et al., 2018). Furthermore, the social dimension of sustainability is often underrepresented (Mahon et al., 2017; Schader et al., 2014), usually not going beyond labour-related considerations (Janker and Mann, 2020). Musumba et al. (2017) and Smith et al. (2017) have recently proposed holistic indicator frameworks for SI assessment, covering a broad range of dimensions at multiple scales. However, these frameworks have been primarily developed for place-based assessments in the context of smallholder farming in developing countries. They do not consider, for instance, the outcomes resulting from larger scale processes, such as market linkages between distant regions and structural shifts in food consumption and production. Such processes may have critical implications for sustainability (Liu et al., 2013). For example, de-intensification of production or increased use of imported inputs (e.g., feed concentrates) at a given location may lead to production reallocation and/or intensification elsewhere (Cadillo-Benalcazar et al., 2020; Fuchs et al., 2020; Wang et al., 2017). These frameworks are therefore not fully applicable to contexts in high-income economies where agricultural production and food consumption are largely integrated in global supply chains and markets.

There is, consequently, a need for developing procedures and criteria to generate analytical frameworks for integrated SI assessment that can provide a comprehensive outlook of sustainability outcomes from local to global scales, while capturing context-specific socio-ecological processes. Such frameworks must be capable of guiding action and supporting broader societal transformations, by providing useful information for deliberation and negotiation. Hence, they need to simultaneously consider the legitimate, but potentially conflicting, normative values and perceptions of different groups of social actors operating at different scales in their specific contexts (Cadillo-Benalcazar et al., 2020). In this article, we aim to address these gaps by presenting a general systematic approach to developing context-specific, multi-scale frameworks for integrated sustainability assessment of agricultural intensity change (Section 2). Any formal assessment of sustainability entails two main steps: i) a pre-analytical step for defining what, out of many alternative and legitimate perceptions, should be considered as the relevant system to be analysed; ii) an analytical decision about how to formalise the system's representation through a finite set of relevant attributes and proxy variables for their quantification (Binder et al., 2010; Giampietro et al., 2006). Hence, we start by proposing a comprehensive system representation for analysing how changes in agricultural intensity lead to multiple sustainability outcomes affecting different societal groups (Section 2.1). We then describe the main steps for identifying the attributes of agricultural intensity and sustainability that are relevant for assessment within a specific context, and for selecting the respective methods and metrics for assessing them (Section 2.2). Finally, we illustrate the proposed approach by developing a multi-scale framework for integrated SI assessment in Europe (Sections 3 and 4), and discuss its strengths and limitations (Section 5).

2. A systematic approach for developing context-specific frameworks for integrated SI assessment

2.1. System representation

Following the conceptual framework for SI pathways proposed by Helfenstein et al. (2020), we start by defining agricultural intensity change (AIC) as the process of adjusting i) management intensity (i.e., the activities, management practices and uses of resources in the farm), and/or ii) landscape structure (i.e., the spatial configuration and composition of agricultural fields and surrounding semi-natural elements and habitats in agro-ecosystems), in order to iii) enhance agricultural productivity (i.e., output per unit of input). Sustainability outcomes (SO) are assumed to evolve relationally through pathways of compound effects resulting from individual processes of AIC (Fig. 1). A number of interrelated socio-ecological processes (SEP) are potentially affected by AIC:

- different types of socio-ecological flows, including biogeochemical cycles and emission of pollutants; people movements (e.g., seasonal/migrant workers, migration of rural population to cities); biological movements (e.g., migratory birds, pollinators, pathogens); trade of agricultural inputs and commodities, and the monetary flows associated with them (Adger et al., 2009; Hull and Liu, 2018);
- the functioning of ecosystems (Emmerson et al., 2016; Stoate et al., 2009)
- different types of socio-ecological interactions, including: social relationships among actors in the farm (e.g., family, workers), members of surrounding communities (e.g., other farmers, neighbours, government officials, collectives) and other (external) actors (e.g., service providers, tourists, consumers) (Janker et al., 2019); species-habitat interactions (Morrison and Dirzo, 2020); human-nature experiences (Soga and Gaston, 2016); and human-livestock interactions (Hostiou et al., 2017).

Changes in these SEP may, in turn, enhance or hinder the ability of agricultural landscapes to deliver bundles of ecosystem services (IPBES, 2019), including regulating (e.g., pollination, freshwater availability), material (e.g., food and feed production) and non-material services (e.g., supporting identities and experiences). The combined effect of changes in SEP and ecosystem service provision (ESP) results in multiple environmental, economic and social outcomes affecting different societal groups, both positively and negatively (Anderson et al., 2019; Blicharska et al., 2019). Feedbacks are established between ESP, SO and AIC, often mediated by concurrent developments in contextual factors (Matson et al., 1997; Meyfroidt, 2013; Meyfroidt et al., 2018). Hence, the effects of AIC on SO need to be assessed along temporal scales long enough (e.g., decades) to capture processes and pathways leading to regime shifts, systemic lock-ins and rebound effects (Giampietro and Mayumi, 2018; Ramankutty and Coomes, 2016; Tappeiner et al., 2020).

The proposed causal framework (see Fig. 1) is largely inspired by the *Driving forces-Pressures-StatesImpactsResponses* (DPSIR) model, originally proposed by the European Environmental Agency (EEA, 2007) and subsequently adopted by multiple international organisations (FAO, 2013; Patrício et al., 2016) to describe and analyse processes and interactions in human-environment systems. However, we make a few important adjustments in relation to the original DPSIR model. Firstly, we explicitly distinguish *Driving forces* in terms of the human activities leading to AIC from the contextual factors that shape them. Secondly, we extend the type of *Pressures* that are typically considered in DPSIR analysis (e.g., the release of pollutants resulting from human activities) to also consider a wider range of SEP, such as the flows of commodities, people and species, and their interactions. As mentioned in Patrício et al. (2016), *Pressures, States* and *Impacts* are not necessarily mutually exclusive categories despite being treated as such, with the distinction often depending on the timeframe considered and scope of the analysis. This has led to varied interpretations on what these components should represent. Rather than attempting to differentiate and characterise these categories, we instead took an outcome-oriented approach which addresses a broad range of SEP and impacts, including changes in ESP (which may or may not affect human activities and well-being) and SO (for which normative ambitions, concerns and/or targets are expressed by different societal groups). Finally, we explicitly consider *Responses* as feedback processes, which may materialise in terms of changes in contextual factors and adjustments in farm management leading to AIC.

Socio-ecological systems express multiple structures and functions in parallel, and within hierarchical levels that are both spatially nested and networked (Adger et al., 2009; Liu et al., 2015; Ostrom, 2009). They can thus be perceived and represented in several non-equivalent ways by distinct groups of social actors. This diversity of perceptions reflects the different norms, beliefs, interests and concerns of these groups, and their respective narratives (*sensu* Giampietro et al., 2006, i.e., the sets of system attributes deemed relevant, and hypothesised causal relations) about how the system should be "improved" (Cadillo-Benalcazar et al., 2020; Lomas and Giampietro, 2017). Hence, multiple scales and levels of analysis need to be simultaneously adopted to capture these

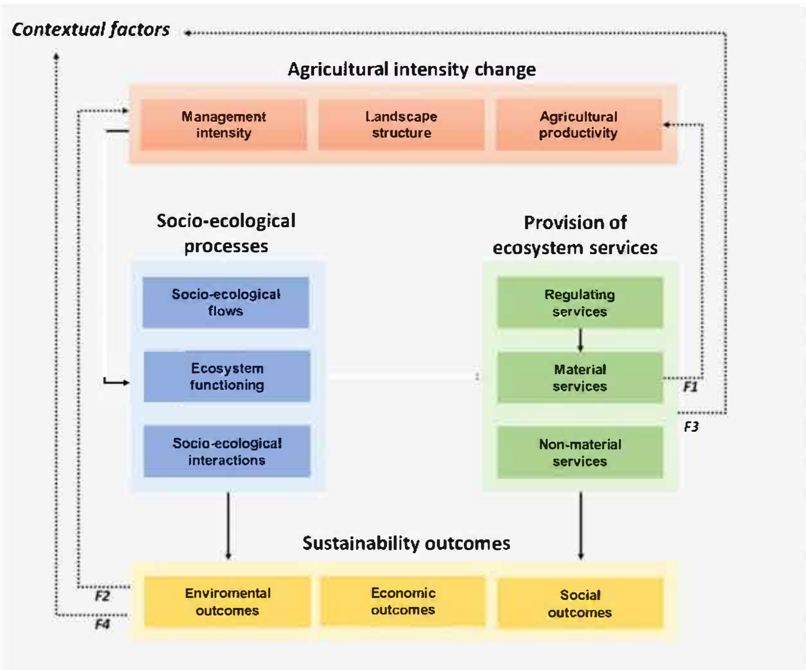

Fig. 1. Pathways of compound effects of agricultural intensity change on sustainability outcomes. Contextual factors (e.g., climate, demography, lifestyle, policy, technology, topography, soil characteristics) affect how these pathways develop over time. Feedback processes (dotted arrows) may emerge due to changes in agricultural productivity resulting from degradation/enhancement of material services (*F1*), changes in agricultural intensity as human-driven responses to sustainability outcomes (*F2*) and broader changes in contextual factors resulting from changes in the provision of ecosystem services (*F3*, e.g., through biogeochemical processes) and from societal developments triggered by sustainability outcomes (*F4*, e.g., demographic changes, policy reforms, technological change, or changes in lifestyle and consumption).

non-equivalent perceptions and narratives. On this basis, we consider the agricultural field, landscape, region and global Earth System as relevant, hierarchically nested geographical scales of analysis for SI assessment (Fig. 2). Rather than fixed entities, these scales are interpreted as constellations of temporary coherence with relatively open territorial boundaries (Wilson, 2009). The agricultural field takes a central place, as the scale at which farm managers execute decisions leading to changes in management intensity (e.g., increasing input application rate) and landscape structure (e.g., increasing field size and removing linear vegetation elements). The landscape scale is instrumental for understanding the socio-ecological context in which farm managers are embedded while making decisions, and assessing the outcomes of these decisions (Helfenstein et al., 2020). Landscapes are here defined as coupled socio-ecological systems characterised by spatially coherent and interrelated sets of natural and anthropogenic components (Angelstam et al., 2019, 2013), including different interacting, and partially overlapping, levels of organisation:

- farms, i.e., decision-making units comprising agricultural fields for crop and livestock production, in which farm managers make decisions on the use of available resources to fulfil a combination of objectives (Malek et al., 2019);
- communities, consisting of actors with different roles, and connected through institutionalised interactions, normative regulations and social relationships defined by work, business and private life (Janker et al., 2019);
- agro-ecosystems, i.e., a complex of plants, animals and microorganisms, their mutual relations, and resulting geographical patterns of landscape structure (Miguet et al., 2016; Tscharntke et al., 2005).

Regions (e.g., countries, sub- and supra-national regions) are relevant scales of analysis because these are usually the administrative units for which political ambitions and (sustainability) targets are set, and progress is monitored. Outcomes in distant "telecoupled" regions, i.e., regions which are not geographically nested but are connected by significant inbound (e.g., food and feed imports) and/or outbound flows (e.g., food exports), are also explicitly considered (Liu et al., 2013). Finally, we consider the global scale to be bounded by the Earth system, and consisting of many smaller coupled social-ecological systems, evolving through time as a set of interconnected complex adaptive systems (Adger et al., 2009; Liu et al., 2015). Assessing outcomes at the global scale is crucial, for example, to identify coordinated solutions for achieving food security without jeopardising the functioning and resilience of the Earth system as a whole (Gerten et al., 2020; Steffen et al., 2015).

2.2. Defining context-specific frameworks for integrated SI assessment

Developing a sustainability assessment framework entails identifying and defining the system attributes that are relevant for different groups of social actors, in order to inform and guide their actions according to their specific sets of expectations, interests and concerns (Cadillo-Benalcazar et al., 2020; Giampietro et al., 2006; Lomas and

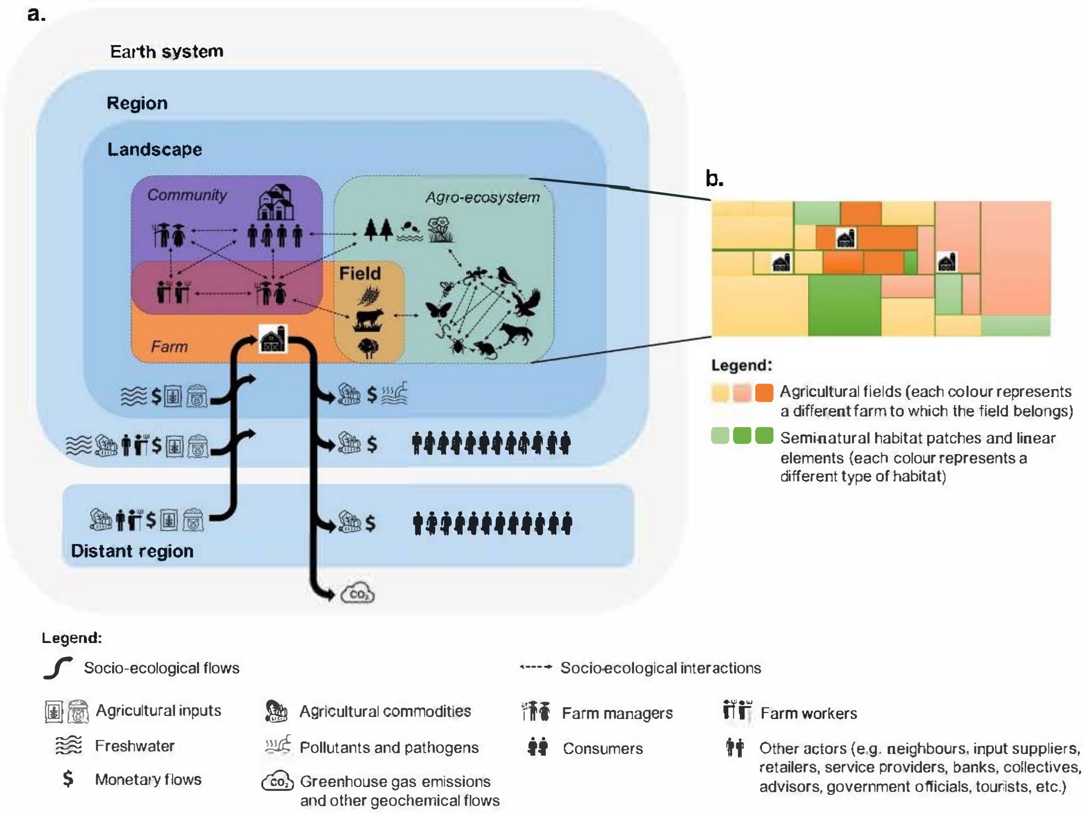

Fig. 2. Geographical scales and organisational levels of analysis for SI assessment. a. Socio-ecological flows and interactions operating across geographical scales (labels in bold) and embedded levels of organisation (labels in italics). Changes in agricultural intensity may trigger or affect a range of inbound and outbound flows, across nested scales from the agricultural field up to the global Earth system, and among networked distant regions. They may also trigger changes in socio-ecological interactions involving different types of actors and species across different organisational levels within the landscape (i.e., farms, communities and agro-ecosystems). b. Landscape structure of agro-ecosystems. Farms are physically composed of a collection of agricultural fields, which may include both adjacent and dispersed fields across the landscape, intertwined with semi-natural habitat patches (e.g., forests, heaths, wetlands) and linear elements (e.g., hedgerows, tree lines, stone walls).

Giampietro, 2017). While developing such frameworks, these system attributes are usually thematically organised in nested hierarchical levels, to facilitate their definition and selection in a structured way (De Olde et al., 2016; Van Cauwenbergh et al., 2007). Adopting the terminology proposed in the FAO-SAFA guidelines (FAO, 2014), we use the following hierarchical levels: dimensions, themes, sub-themes and indicators. Following the system representation presented in Section 2.1, we start by designating *Agricultural intensity*, *Ecosystem service provision* and *Sustainability outcomes* as the core dimensions for the development of the analytical framework. The lower hierarchical levels of these dimensions are then specified by identifying the attributes and metrics that enable the assessment of how AIC affects, through changes in SEP and ESP, a multitude of SO. Accordingly, we propose the following steps (Fig. 3):

- **Step 1:** Identify the mechanisms of agricultural intensity change (MAIC) that are applicable to a particular context. MAIC are defined as the adjustment of a particular set of attributes of management intensity or landscape structure that affects agricultural productivity by causing changes in the output/input ratios, i.e., agronomic productivity, resource-use efficiency and/or profitability. Based on the identified mechanisms, relevant themes, sub-themes and indicators are defined for the *Agricultural intensity* dimension that permit the assessment of these mechanisms quantitatively.
- **Step 2:** Identify the potential effects of the identified MAIC on context-specific SEP, leading to changes in ESP. Relevant themes, sub-themes and indicators are then defined for the *Ecosystem service provision* dimension.
- **Step 3:** Identify the potential effects of the identified MAIC on SEP and ESP, leading to a range of SO that are relevant to different groups of social actors. Relevant themes, sub-themes and indicators are then defined for the *Sustainability outcomes* dimension. The combined results of Steps 1, 2 and 3 allow the definition of the context-specific hierarchical structure of SI indicators.
- **Step 4:** Identify available methods and data sources to compute metrics for the SI indicators defined in the previous steps. The selected metrics enable the definition of the context-specific framework for integrated SI assessment.

3. Material and methods

We illustrate the application of the approach presented in Section 2 by developing a multi-scale indicator framework for SI assessment in Europe. In particular, we apply the approach through a stepwise literature review, for each core dimension in turn, as follows:

- **Step 1:** the *Agricultural intensity* dimension was defined by conducting a literature review, combined with inductive content analysis (Khirfan et al., 2020), to identify the main MAIC in Europe. Firstly, we searched for peer-reviewed articles describing cases with changes in agronomic productivity, resource-use efficiency and/or profitability in Europe. Appendix A describes in detail the literature search strategy and criteria for selecting articles. Based on the literature analysis, we developed a MAIC typology, and identified sets of attributes that characterise them (see Table A.1). Based on these results, we defined *Agricultural intensity* themes, sub-themes and indicators.
- **Step 2:** the *Ecosystem service provision* dimension was defined by conducting a literature review, combined with deductive content analysis (Kyngäs and Kaakinen, 2020), to identify the effects of AIC on ESP in Europe. Appendix B describes in detail the literature search strategy, criteria for selecting articles and approach for conducting the literature analysis. We used the IPBES Nature's Contributions to People (NCP) framework (Díaz et al., 2018, 2015) as a heuristic to specify the hierarchical structure of this dimension. The NCP framework has been jointly developed by academia, governments and civil society, building upon the ecosystem service concept (Millennium Ecosystem Assessment, 2005), while emphasising the importance of cultural context as a central factor for shaping human

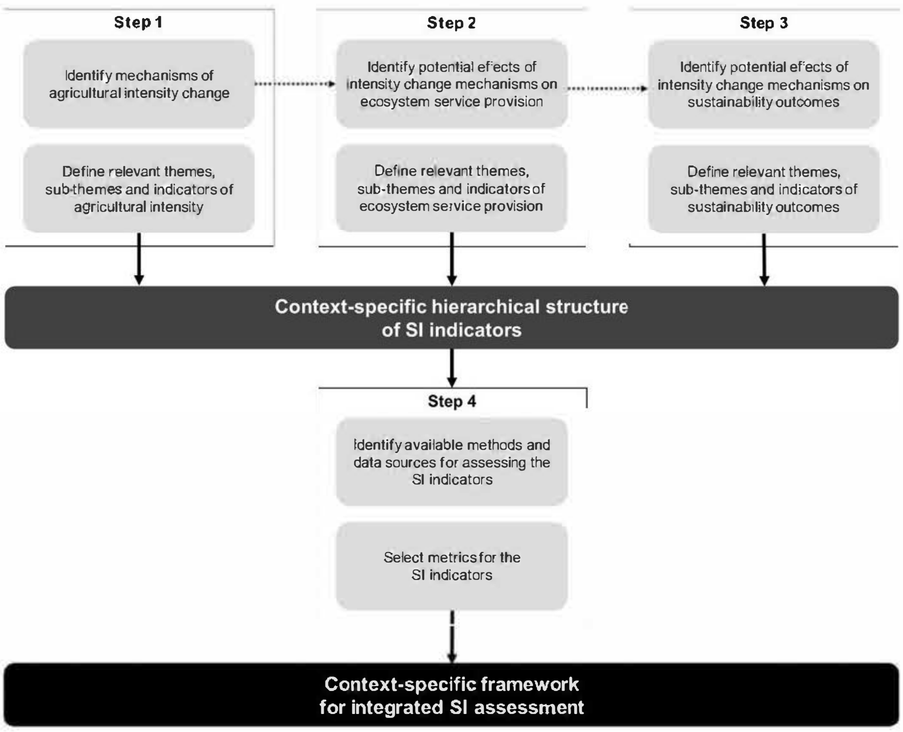

Fig. 3. Approach for developing context-specific frameworks for integrated SI assessment.

perception of nature and quality of life (Díaz et al., 2018; Peterson et al., 2018). The sets of ecosystem service categories defined by the NCP framework were used as a guiding principle for defining the *Ecosystem service provision* themes (i.e., NCP types) and sub-themes (i.e., NCP reporting categories; for their definitions, see Table B.1 in Appendix B), and accordingly guide the content analysis of the selected literature. We then identified the effects of each MAIC on each NCP reporting category (Tables B.2, B.3 and B.4 in Appendix B). Based on these results, for each sub-theme we defined a set of key attributes as *Ecosystem service provision* indicators.

- **Step 3:** the *Sustainability outcomes* dimension was defined through literature review, combined with deductive content analysis, on the effects of AIC in Europe on SO. We used the United Nations Sustainable Development Goals (SDG) framework (UN, 2015) as a heuristic to specify the hierarchical structure of this dimension. The SDG framework has been developed through a comprehensive participatory process (UN, 2014; UNDG, 2013), representing a compromise between a multiplicity of concerns and interests from different societal groups. Hence, the SDGs provide a comprehensive mapping of a broad universe of legitimate, but potentially conflicting, normative visions of sustainability (Le Blanc, 2015). This, in turn, provides an appropriate guiding principle for defining the *Sustainability outcome* themes (i.e., SDG goals) and sub-themes (i.e., SDG targets). We adapted the list of keywords of the SDG literature search queries proposed by the Aurora Universities Network (AUN, 2021) to define search strings. Appendix C describes in detail the literature search strategy, criteria for selecting articles and approach for conducting the literature review. The results of the literature analysis were used to identify the effects of each MAIC on SO related to each SDG goal (Tables C.2, C.3 and C.4 in Appendix C) and the societal groups to which they are relevant. Based on these results, for each sub-theme we defined a set of key attributes as *Sustainability outcome* indicators.
- **Step 4**: we reviewed existing literature to identify applicable methods and metrics to measure the indicators defined in the previous steps at different scales in Europe. In addition, we also reviewed online data portals from international agencies and organisations to identify available data sources with pan-European coverage. Appendix D.1 describes in detail the search strategy and criteria for the review of literature and databases.

4. Results

4.1. Assessing agricultural intensity change in Europe (Step 1)

We identified thirteen MAIC operating in Europe (Table 1; for a detailed overview and references, see Table A.1 in Appendix A). Many of these mechanisms are often observed in combination with others. For example, an increase in capital intensity typically occurs together with an increase in land management intensity, input-use intensity, farm concentration and a certain degree of farm specialisation. Some mechanisms may result in the de-intensification of other attributes. For example, increased capital intensity and improved information management through the adoption of robotics for precision farming contributes to lower input-use intensity. Product differentiation, vertical integration, income diversification and cooperation enable increased profitability and reduced risks through economies of scope and/or added-value creation, without necessarily increasing physical production.

Agricultural Intensity sub-themes and indicators were specified based on the identified attributes of management intensity, landscape structure and agricultural productivity (Table 2). Land management indicators are primarily measured at the agricultural field scale. Consumable input use and agronomic productivity indicators can be measured at the field scale (e.g., to assess relationships between field productivity and management intensity), but they are equally relevant

Table 1
Mechanisms of agricultural intensity change (MAIC) operating in European agriculture.

MAIC	Description
Land management intensity	Adjusting the intensity of land management practices (e.g., livestock density, grazing period length, crop rotation cycles, cropping density, intercropping) and frequency of field management operations (e.g., soil tilling, grassland mowing, mechanical weeding, orchard pruning, soil drainage).
Capital intensity	Adjusting investments in fixed capital assets such as buildings (e.g., silos, stables, greenhouses), infrastructure (e.g., irrigation, roads), machinery and equipment (e.g., mechanic plough, automatic feeder, milking robots, drones), permanent crops (e.g., tree orchards), livestock herd size, and land reclamation (e.g., permanent drainage of wetlands).
Input-use intensity	Adjusting the use of consumable inputs such as fertilisers, pesticides, animal feed and health inputs, seeds, water and energy.
Labour intensity	Adjusting labour inputs, including family and hired labour (permanent and seasonal).
Farm consolidation	Achieving increasing returns to scale/size through enlargement of farm size (e.g., buying/renting land from other farms), land consolidation (e.g., reallocating land to make farms more compact) and landscape simplification (increasing field size by removing semi-natural habitat patches and linear landscape elements).
Farm specialisation / diversification	Adjusting crop diversity, and/or the diversity of livestock species, breeds and stages of animal development. In the case of specialisation, resources are concentrated on a limited number of activities for which local conditions and available resources are optimal. In the case of diversification, economies of scope are achieved by engaging in complementary activities (e.g., mixed crop-livestock systems) or cultivating complementary crops (e.g., nutrient fixating crops, cover crops, different types of forage crops).
Income diversification	Diversifying the number of activities and income sources, including agro-environmental activities (particularly, when they are supported by financial compensation schemes), non-farming activities (e.g., agritourism, gastronomy, renting idle farm equipment, renting land for renewable energy production) and off-farm employment.
Regional specialisation and concentration	Achieving agglomeration benefits through clustering of similar farm activities in regions where industrial/logistic hubs for processing, transporting or marketing agricultural products exist (e.g., dairy industry, vegetable oil production, harbours, auctions).
Vertical integration	Reducing transaction costs and risks through contract farming, and/or consolidation of production, processing and marketing operations (e.g., direct marketing).
Knowledge intensity change	Acquiring knowledge and skills to improve management practices through education and training, and/or consultation with advisory/extension services.
Improved information management	Adjusting planning (e.g., seeding, harvesting), process controlling (e.g., milking operations), resource-use (e.g., fertiliser use), and/or marketing strategies (e.g., sales) using information and communications technology (ICT).
Crop/breed change and product differentiation	Switching to higher productivity varieties, high-value products or added-value niche markets (e.g., organic farming, protected designation of origin, voluntary sustainability standards).
Cooperation	Achieving economies of scale and/or scope based on social capital (e.g., jointly governing resources, infrastructure, services, knowledge, value chains, and/or marketing strategies).

Table 2
Themes, sub-themes and indicators for assessing agricultural intensity (AI) in Europe.

AI theme	AI sub-theme	AI indicators	Scale/level of measurement[a]	MAIC[b]
Management intensity	Land management	Livestock density; Grazing period length; Frequency of field operations; Cropping frequency; Fallow cycle frequency; Sowing density; Intercropping; Crop rotation	AFS	LMI; FSD
	Fixed capital assets	Irrigation area; Irrigation equipment; Machinery and equipment; Buildings and infrastructure; Permanent crop area; Permanent crop density; Herd size; Breeding livestock; Milking livestock; Livestock replacement rate; Land ownership structure;	FL	CI; IIM
	Consumable inputs	Fertiliser use; Fertiliser composition; Pesticide use; Pesticide toxicity; Feed intake; Feed composition; Animal health inputs use; Water use; Energy use; Seeds inputs;	AFS; FL	IUI
	Labour	Labour input; Family labour; Hired labour; Permanent/seasonal labour; Employee turnover	FL	LI
	Farm size	Farm area; Farm economic size		FC
	Human capital	Farmer education and training; Workers training; Consultation with advisory/ extension services		KI; IIM
	Farming diversity	Crop types and varieties; Livestock species and breed varieties; Stages of animal development;		FSD; RSC; CCPD
	Income sources	Farming income; Non-farming income; Off-farm income; Subsidies; Diversity of income sources		ID
	ICT use	ICT services use frequency; Computer literacy		IIM; KI
	Value chain and product value added	Value-chain position; Contract farming; Processed products; By-products; Organic farming; Regional product certification; Voluntary sustainability standards		VI; CCPD
	Social capital	Membership in organisations;		C
Landscape structure	Landscape composition	Agricultural land-use composition; Semi-natural habitat composition;	FL; LS	FC; LMI; CI; FSD; RSC; ID
	Landscape configuration	Agricultural field size; Distance of fields to the farmhouse; Semi-natural habitat patch size; Density of landscape elements; Density of historical/cultural landmarks		FC; CI
Agricultural productivity	Agronomic productivity	Crop yield; Grassland yield; Yield variability; Animal productivity	AFS; FL	LMI; CI; IUI; LI; FC; FSD; KI; IIM; KI; CCPD
	Resource-use efficiency	Input efficiency; Nutrient efficiency; Labour efficiency; Energy efficiency; Water efficiency; Feed efficiency; Input self-sufficiency		All mechanisms
	Profitability	Economic output; Economic added-value; Total output; Total output variability;	FL	All mechanisms

[a] Scales and levels of organisation: AFS – Agricultural field scale; FL - Farm level; LS - Landscape scale.
[b] Mechanisms of agricultural intensity change: LMI - Land management intensity; CI - Capital intensity; IUI - Input-use intensity; LI - Labour intensity; FC - Farm consolidation; FSD - Farm specialisation / diversification; RSC - Regional specialisation and concentration; VI - Vertical integration; KI - Knowledge intensification; IIM - Improved information management; CCPD - Crop change and product differentiation; ID – Income diversification; C - Cooperation.

at the farm level to assess of the overall resource-use efficiency of the farm. All other management intensity and agricultural productivity indicators are primarily assessed at the farm level. Provided that the number and stratification of the sample is representative, indicators at the farm level can be aggregated at the landscape and regional scales to identify broader structural changes in agricultural intensity.

Landscape structure indicators are primarily assessed at the landscape scale, to reveal potential causal linkages between alterations in landscape structure and changes in the provision of ecosystem services (see Section 4.2). However, some indicators are also relevant at the farm level in order to distinguish the magnitude effects of intensity change processes of individual farms within the landscape.

4.2. Assessing the effects of agricultural intensity change on ecosystem service provision in Europe (Step 2)

We identified the effects of the different MAIC operating in Europe in the provision of fourteen ecosystem services (Fig. 4; for a detailed overview and references, see Tables B.2, B.3 and B.4 in Appendix B), and accordingly specified indicators to assess these effects (Table 3). Most ecosystem services are directly mediated by the provision of habitat creation and maintenance, due to the role of agricultural farmland and semi-natural vegetation in providing regulating functions (i.e., climate, water, air quality, and extreme event regulation) or habitat for the organisms facilitating them (e.g., pollinators, soil regulating biota, pest control organisms). Therefore, MAIC that alter habitat composition, biotic interactions and overall ecosystem functioning through changes in landscape structure and/or increased flows of pollutants (including surplus of nutrients) have significant effects on bundles of regulating services. These combined effects on regulating services may partially negate the positive effects of MAIC enhancing material services (i.e., energy, food and feed provision), potentially leading to further adjustments in agricultural intensity as a response. In addition, mechanisms that affect habitat creation and maintenance may also affect human-nature interactions, leading to changes in the provision of non-material services (i.e., supporting identities, experiences and learning). These may, in turn, trigger societal responses. Ecosystem service provision indicators are primarily assessed at the landscape scale, though soil regulation, detrimental organism regulation and material services are also appropriately assessed at the field scale.

4.3. Assessing the effects of agricultural intensity change on sustainability outcomes in Europe (Step 3)

Based on the SDG framework, we identified twelve themes of SO that are affected at multiple scales by the MAIC operating in Europe. In this section we provide a summary of these effects; for a detailed overview and references, see Tables C.2, C.3 and C.4 in Appendix C. The respective sustainability outcome indicators are specified in Table 4.

All MAIC affect the aggregated production and trade flows of agricultural commodities, thus influencing outcomes related to SDG2 (End hunger) and SDG7 (Access to energy), i.e., food and energy availability, affordability, self-sufficiency and supply stability. These outcomes are primarily assessed at the regional scale, including distant regions connected through trade flows. The aggregated patterns of production, trade and consumption are also pivotal for outcomes related to SDG12 (Sustainable consumption and production), which is assessed with the indicators land, water and material footprints of food consumption at regional and global scales. Land management, capital and input-use intensification in livestock production affect animal welfare and health. Such outcomes are also included in the SDG12 theme.

All mechanisms also bring about changes in monetary flows to and from the farm. Consequently, they affect outcomes at the farm level related to SDG1 (End poverty), particularly farm household income levels, and overall farm resilience (i.e., income stability, viability, adaptability and autonomy). Mechanisms that operate through economies of size and scale may also trigger rebound effects leading to structural changes at broader scales. For example, increased production within a region due to widespread capital, land management and input-use intensification may drive commodity prices down, putting additional competitive pressure on smaller farms, and potentially undermining their viability. Such processes thus affect outcomes related to SDG10 (Reduce inequality). Indicators that assess income levels and inequality at the regional scale are thus included in SDG1 and 10 themes, respectively.

Income and farm resilience, in turn, play an important role in outcomes related to SDG3 (Health and well-being), due to potential psychological distress experienced by farm households because of high levels of debt (e.g., due to high capital intensity) and irregular monetary flows (e.g., due to price volatility). In addition, long working hours can cause injuries, be mentally stressful, and reduce opportunities for social interaction, and therefore have a potential effect on farmers' and workers' physical and mental health. Input-use intensification increases health risks to farm managers and workers due to increased exposure to pesticides during handling and spraying, and to surrounding communities through spray drift. It also leads to a high concentration of pollutants in surface and groundwater resources, thus posing health risks to communities that extract drinking water directly from the environment. In addition, it may also increase consumers' exposure to toxic chemicals in food. Increased livestock density causes the degradation of air quality through emissions of particulate matter, leading to increased risks of respiratory diseases. It also increases the transmission risk and virulence of zoonotic diseases and antimicrobial-resistant bacteria to both surrounding communities and consumers. Indicators at the farm level, community level and regional scale are thus included as part of SDG3, to assess the respective health outcomes in different groups of actors.

Aggregated monetary flows and labour demand within a region have important effects on the economic output and employment of agriculture and other related sectors (e.g., input suppliers, retailers, service providers, food processing), thereby affecting regional-scale outcomes related to SDG8 (Economic growth and employment). High unemployment resulting from a structural decrease in labour intensity may drive (young) people to migrate to urban areas, leading to a shrinking and ageing population. Concurrently, labour-intensive farms (e.g., horticulture specialists) rely on low-cost seasonal workers, often of migrant origin. Human and labour rights violations, limited health protection, precarious housing conditions, and social exclusion are often reported. Such processes and the resulting changes in social interactions play an important role in the quality of life and social cohesion of rural communities. As a result, indicators that assess these aspects are included in the theme SDG11 (Sustainable cities and communities). In addition, women are often worst affected when unemployment in rural areas is high, which is then amplified by unbalanced responsibilities in terms of household caring duties. Hence, indicators that assess women's unemployment and migration are also included as part of SDG5 (Gender equality).

Mechanisms affecting non-material services, combined with capital intensification (e.g., replacing historical farm buildings with modern facilities), and specialisation/diversification (e.g., abandonment/uptake of traditional farm practices and local varieties), may affect not only the cultural heritage, sense of place, and quality of life of surrounding communities, but also the potential for tourism and gastronomy. Hence, indicators that assess these outcomes at the community level and regional scale are included in the themes SDG11 and 8, respectively.

Combinations of MAIC that cause changes in water use, flows of excess nutrients and chemicals, and the provision of water regulating services contribute to outcomes related to SDG6 (Clean water), which can be assessed with indicators of freshwater availability and quality at the landscape and regional scales. Mechanisms that contribute to changes in landscape structure and the provision of regulating services play a significant role in outcomes related to SDG15 (Sustainable terrestrial ecosystems), assessed with indicators of biodiversity, land degradation and deforestation. Several mechanisms affect SDG13 (Climate action) by contributing to direct and indirect GHG emissions at the farm level. In addition, changes in land management intensity have an impact on soil carbon content, farm consolidation affects carbon sequestration, while drainage and irrigation contribute to the release of nitrous oxide and carbon dioxide. Indicators that assess these effects at the field and landscape scales are thus also included. Finally, the overall carbon footprint of the food system can be assessed at regional and global scales, considering total GHG emissions from production to consumption.

4.4. Selecting SI indicator metrics (Step 4)

Based on the three previous steps, we defined the hierarchical structure of the indicator framework for SI assessment in Europe (i.e., Tables 2, 3 and 4 combined). Indicator metrics were then selected for each indicator at their respective scales/levels of measurement. The resulting multi-scale framework for SI assessment in Europe is presented in Appendix D.2 (Tables D.3, D.4 and D.5), including references to methods and data sources.

Most farm- and community-level indicator metrics on agricultural intensity change and socio-economic sustainability outcomes (i.e., SDG1, 3, 10, 11 and 12) can be derived through farm surveys and stakeholder interviews. Indicator metrics related to farm accounting (i.e., resource-use efficiency, profitability, SDG1 and 10) can be derived from official national surveys, such as those collected by the EU Farm Accountancy Data Network, which also provides aggregated metrics at the regional scale for different farm typologies.

Several methods are available to derive indicator metrics at the field and landscape scales for landscape structure, ecosystem service provision and environmental sustainability outcomes (i.e., SDG6, 13 and 15), including: field surveys, stakeholder interviews, remote sensing, volunteered geographic information, environmental monitoring and spatial modelling. International initiatives have recently developed harmonised indicator metrics for biodiversity assessment at the regional and global scales (BIP/CBD, 2010; GEO BON, 2017; OECD, 2019). Ecosystem service accounting is also increasingly receiving attention from both EU and global governance initiatives aiming at developing accounting systems at the country and sub-national levels (e.g., UNCEEA, 2021; Vysna et al., 2021).

Environmental sustainability outcomes related to production and consumption patterns (i.e., SDG12 and 13) can be derived at the farm level through life-cycle assessment, and at regional and global scales through environmental footprint assessment, and material and energy flow accounting methods that link remote sensing with trade data. Finally, regional- and global scale indicator metrics on sustainability outcomes related to SDG2, 7, 8 and 11 are typically made available in online data portals from official statistics offices and international agencies and organisations.

The selected indicator metrics can then be implemented within a decision-support tool with visualisation systems such as dashboards or scorecards. Ideally, these tools should enable different groups of social actors to visualise, for instance, (combinations of) interventions that render improvements from their perspective but negative consequences for concerns prioritised by other social actors (Cadillo-Benalcazar et al., 2020). Such tools should thus be equipped with a user interface open to semantic control (i.e., with the ability to flexibly select and manipulate the information relevant for a particular task), so that sub-selections of indicators can be thematically organised. This could be done, for example, in terms of the groups of actors for which the indicators are relevant, and the scales at which the outcomes are manifest. This means not only organising and distinguishing indicators for different types of

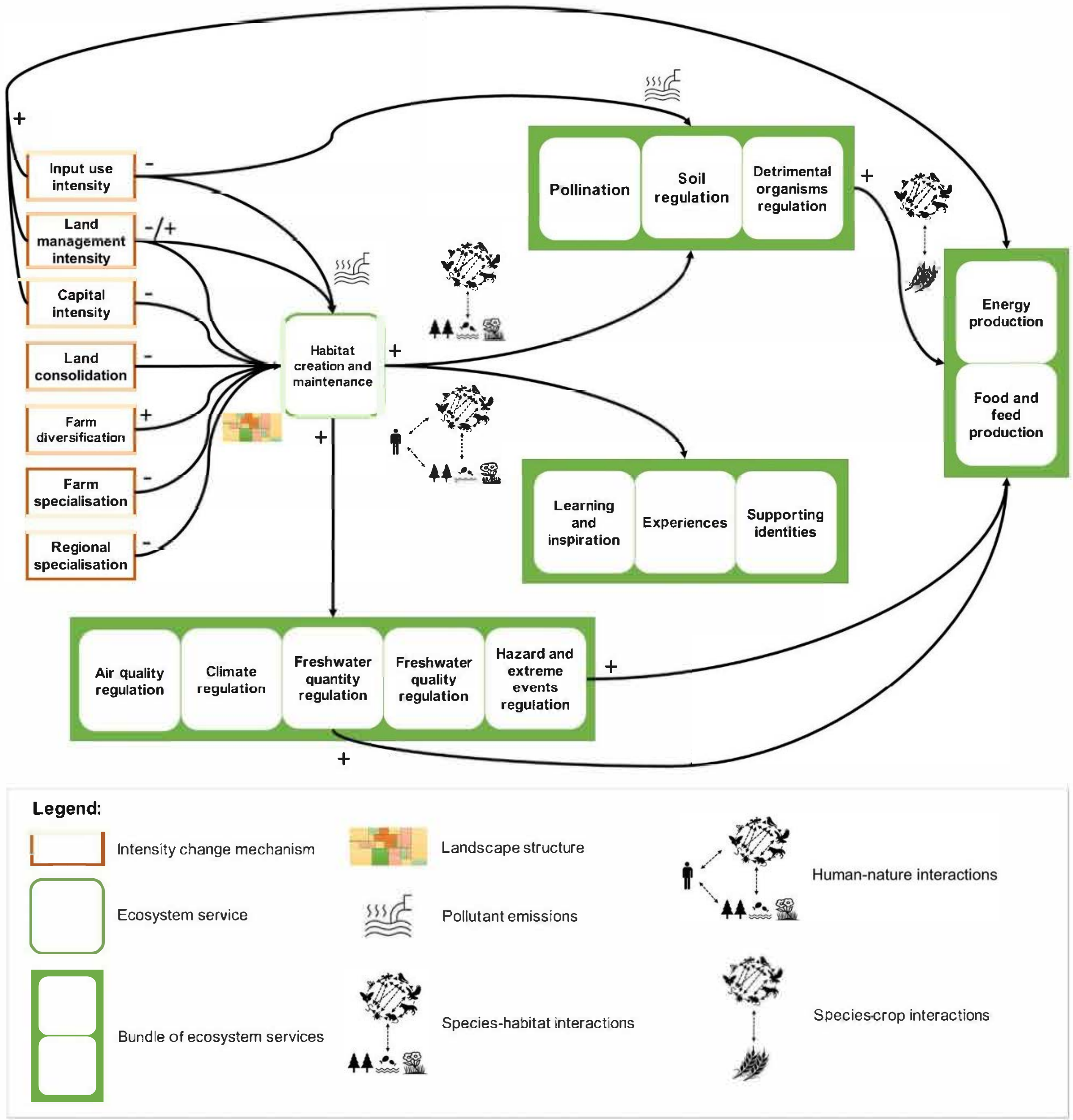

Fig. 4. Identified effects of mechanisms of agricultural intensity change on the provision of ecosystem services in Europe (feedback processes in terms of human-driven responses to changes in the provision of ecosystem services are not depicted).

actors (e.g., farmers, workers, rural communities, consumers) but also disaggregating indicator metrics for similar types of actors with different sets of characteristics (e.g., type of production system, income level, region), in order to identify how (structural) changes in agricultural intensity may affect similar types of actors in unequal ways (Broegaard et al., 2017; Dawson et al., 2019, 2016; Rasmussen et al., 2018; Suwarno et al., 2016). It is also important to allow for metrics with different units of measurement for the same indicator. Seufert and Ramankutty (2017), for example, identified contrasting findings in terms of environmental performance of organic agriculture when assessing impacts per unit of area and per unit of product. For guidelines on designing and encoding visualisations representing socio-ecological processes and outcomes, and analysing and visualising multi-scale sustainability trade-offs, we refer to Sonderegger et al. (2020) and Kanter et al. (2018), respectively.

5. Discussion and conclusions

The proposed approach provides a clear rationale for identifying attributes that are relevant for the assessment of SI in a particular context, and their respective scales of measurement, based on the explicit identification of relevant system boundaries, socio-ecological processes, groups of actors and their respective stakes. In this way, the

Table 3
Themes, sub-themes and indicators for assessing ecosystem service provision (ESP) in Europe.

ESP themes	ESP sub-themes	ESP indicators
Regulating services	Habitat creation and maintenance	Habitat availability; Habitat connectivity; Habitat fragmentation; Habitat quality; Net primary production; Temporal stability
	Pollination	Pollination potential
	Air quality regulation	Air pollution retention capacity
	Climate regulation	Carbon sequestration potential; Albedo; Evapo-transpiration; Temperature regulation; Humidity regulation
	Water quantity regulation	Water flow regulation capacity
	Water quality regulation	Water pollution filtration capacity
	Soil regulation	Soil erosion regulation capacity; Soil nutrient fixation capacity; Sediment retention capacity
	Extreme events regulation	Flood regulation capacity; Wind regulation capacity; Fire regulation capacity;
	Detrimental organisms regulation	Natural pest control potential;
Material services	Energy production	Potential crop yield for bioenergy crops
	Food and feed production	Potential crop yield for food crops; Potential crop yield for feed crops;
Non-material services	Learning and inspiration	Landscape educational value;
	Physical and psychological experiences	Landscape aesthetic value; Landscape recreational value
	Supporting identities	Cultural heritage value; Landscape spiritual value

most common shortcomings of existing SI assessment frameworks are addressed, particularly the incomplete coverage of sustainability dimensions and chains of causal effects, and arbitrariness in the definition and selection of indicators and scales of measurement (Janker and Mann, 2020; Mahon et al., 2017; Schader et al., 2014). Scown and Nicholas (2020), for example, found that the current EU Common Agricultural Policy monitoring system is unable to conduct a balanced assessment of many of its potentially competing goals because its selection of indicators is biased towards only a few objectives.

Defining agricultural intensity broadly in terms of output/input ratios enabled the identification of a diverse range of MAIC beyond land-use intensification. This is in line with the conceptual framework of SI fields of action proposed by Weltin et al. (2018), which, similarly to our framework, also accounts for intensity change strategies based on resource-use efficiency and added-value generation. Such mechanisms are highly relevant as they provide farmers with potentially viable strategies for improving their income and coping with ongoing structural changes (i.e., scale enlargement, with diminishing margins) in European agriculture (Maucorps et al., 2019; Tocco et al., 2015).

The SDG framework provided a useful heuristic for identifying normative dimensions representative of the aspirations and concerns of different groups of actors in Europe. While many of the identified sustainability themes bore similarities to existing frameworks (e.g., farm income, biodiversity, water pollution, climate change– see, for example, Van Cauwenbergh et al., 2007, FAO, 2014, Smith et al., 2017), our approach revealed a number of additional outcomes that are rarely considered in SI assessments. This included, for example, farm house holds' (mental) health, seasonal workers' health and living conditions, animal welfare, cultural heritage and sense of place of rural communities, impacts on economic sectors not directly related to agriculture (e.g., tourism), shrinking and ageing of rural population, energy security, and consumers' health. These sustainability themes are central to recent European-wide policy initiatives, such as the *European Green Deal* (EC, 2019) and the *Farm to Fork Strategy* (EC, 2020), and ongoing debates on the sustainability of European agriculture (e.g., Bartz et al., 2019; Navarro and López-Bao, 2018; Pe'er et al., 2020, 2019, 2017, 2014). These results underpin the usefulness of the generated framework towards informing deliberations in the context of European agriculture.

The development of the framework also revealed the importance of structural feedbacks of production and consumption that operate across nested scales and distant regions, thus reiterating the need for envisioning SI pathways that coordinate transformative changes both in the supply and demand side of food systems (Cadillo-Benalcazar et al., 2020; Fuchs et al., 2020; Poore and Nemecek, 2018; Renner et al., 2020; Scherer et al., 2018). Many of these processes and effects are also relevant in non-European contexts, thus underlining the utility of our approach for generating SI assessments generally.

The concept of multifunctionality is strongly associated to that of sustainability, particularly in relation to agricultural landscapes and their ability to sustain ecological functions, economic development and the well-being of rural communities (O'Farrell and Anderson, 2010; Stoate et al., 2009; Wilson, 2010, 2009). Although we have not explicitly addressed it here, many of the proposed indicators facilitate the evaluation of landscape multifunctionality, and respective outcomes over a wide range of sustainability themes. Analysing the multifunctionality of agri-food value chains is also relevant for sustainability, as it can expose strategic and operational misalignments within chains, misallocation of resources, and opportunities for creating not only economic, but also environmental and social value (Fearne et al., 2012; Porter and Kramer, 2011). Hence, we recognise that the present approach could benefit from a more explicit representation of value chain networks, and respective indicator metrics to measure multifunctional value along them, from farmer to consumer (e.g., Fagioli et al., 2017).

We illustrated the proposed approach by generating a framework specifically tailored to the European context. Europe as a whole was thereby considered as a "context", to the extent that it is a world region where many countries share standardised systems of laws, regulations and policy frameworks, a single common market, an advanced agricultural sector integrated into global supply chains and, to some degree, similar sets of principles, values and lifestyles. However, Europe is also characterised by a large degree of heterogeneity in terms of geographical features, cultural manifestations and historical legacies. On this basis, one could instead argue that it is actually composed of a patchwork of diverse (sub-)contexts. Two interrelated challenges would arise, if the framework were intended to be fully operationalised in a uniform way across Europe. Firstly, only a few studies may have the time, resources and/or expertise to fully evaluate such an exhaustive set of attributes for an entire continent. Thus, some degree of prioritisation may be required when selecting the attributes, processes and sustainability dimensions to be evaluated. In fact, not all indicators are necessarily relevant for quantification in every European sub-context. The framework presented here should, therefore, not be regarded as a "one-size-fits-all" assessment tool to be uniformly operationalised, but rather as a decision-support tool open to semantic control for selecting indicators in function of the goals and scope of analysis. For example, regional scale indicators can be selected to uniformly assess trends and benchmark outcomes across regions for the whole of Europe, using metrics available in public online databases or produced with large-scale models (e.g., Cerilli et al., 2020; Debonne et al., 2022). Indicators at the landscape scale and farm level should be specifically selected for sub-contexts based on their relevance (e.g., depending on the existing types of agro-ecosystem, ongoing processes of intensity change, and the priorities and concerns of different local groups of actors), and then evaluated in place-based assessments. In such settings, the generated framework can offer a structured procedure to conduct integrated multi-scale SI assessments for a variety of sub-contexts within the larger European context, and accordingly evaluate the extent to which local aspirations and developments in different locations converge/diverge towards broader regional targets, global priorities and societal visions (e.g., Helfenstein et al., 2022).

Table 4
Themes and indicators for assessing sustainability outcomes (SO).

SO themes	SO indicators	Scales/levels of measurement[a]	MAIC[b]	Socio-ecological processes	Mediating ecosystem services	Relevant actors
SDG1 – End poverty	Income level; Income stability; Farm viability; Farm adaptability; Farm autonomy	FL; RS;	All mechanisms	Commodity and monetary flows	Regulating and material services	Farm managers and households; Workers
SDG2 – Zero hunger	Food availability; Affordability; Supply stability; Self-sufficiency; Safety; Nutrition security; Food security	RS; DR	All mechanisms	Commodity and monetary flows	Regulating and material services	Consumers
SDG3 - Health and well being	Mental health; Physical injuries; Occupational exposure to pesticides; Zoonotic diseases; Respiratory illnesses	FL	All mechanisms	Private and work interactions; Livestock-human and human–nature interactions; Monetary, pollutant and pathogen flows	-	Farm managers and households; Workers
	Environmental exposure to pesticides; Exposure to nitrates in drinking water; Zoonotic diseases; Respiratory illnesses	CL	LMI; CI; IUI	Water, pollutant and pathogen flows	Air quality regulation; Water quality regulation	Communities
	Dietary exposure to pesticide residues and heavy metals; Food-borne diseases	RS	LMI; CI; IUI	Commodity flows	-	Consumers
SDG5– Gender equality	Women unemployment; Women migration	RS	CI; LI; FC	Private and work interactions; Migration flows	-	Farm households; Communities
SDG6– Clean Water	Freshwater availability; Freshwater quality	LS; RS	LMI; CI; IUI; FC; FSD; RSC; IIM	Water, pollutant and pathogen flows	Water and soil regulating services	Farm managers; Communities
SDG7– Clean Energy	Energy security	RS; DR	All mechanisms	Commodity and monetary flows	Regulating and material services	Consumers
SDG8– Work and economic growth	Economic output agriculture; Economic output tourism; Regional economic output; Regional unemployment	RS	All mechanisms	Commodity, monetary and people flows	All ES	Farm managers; Communities; Agriculturerelated sectors: Tourists
SDG10 – Reduced inequality	Income inequality; Income stability; Farm adaptability; Farm autonomy; Poverty	CL; RS	All mechanisms	Commodity and monetary flows	Regulating and material services	Farm managers and households; Workers; Communities
SDG11 – Sustainable cities and communities	Social cohesion; Workers' rights; Quality of life; Sense of place; Rural population; Air quality	CL; RS	All mechanisms	Migration flows; Private, work and business interactions; Human-nature interactions; Pollutant flows	Regulating and nonmaterial services	Communities; Farm workers
SDG12 – Sustainable production and consumption	Animal health and welfare	FL; RS	LMI; CI; IUI	Human-livestock interactions	-	Farm managers; Workers; NGOs; Consumers
	Land footprint; Water footprint; Nutrient footprint; Material footprint	RS; DR	LMI; CI; IUI; FC	Commodity flows		Consumers
SDG13 – Climate action	Carbon storage; Soil nitrous oxide emissions	AFS; LS	LMI; IUI, FC;	GHG flows	Climate regulation	Farm managers; Consumers
	Carbon footprint	FL; RS; GS	All mechanisms			
SDG15 – Sustainable terrestrial ecosystems	Land degradation	AFS; RS	LMI; CI; IUI; FC; FSD; RSC; CCPD	Ecosystem functioning; Species migration; Pollutant flows	Regulating services	Farm managers; Nature conservation
	Deforestation; Ecosystem degradation	LS; RS; DR				
	Water biodiversity; Soil biodiversity; Above-ground biodiversity	AFS; LS; RS; DR; GS				
	Functional biodiversity	LS				

[a] Scales and levels of organisation: AFS – Agricultural field scale; FL - Farm level; CL - Community level; LS - Landscape scale; RS - Regional scale; DR – Distant region GS - Global scale.

[b] Mechanisms of agricultural intensity change: LMI - Land management intensity; CI - Capital intensity; IUI - Input-use intensity; LI - Labour intensity; FC - Farm consolidation; FSD - Farm specialisation / diversification; RSC - Regional specialisation and concentration; VI - Vertical integration; KI - Knowledge intensification; IIM - Improved information management; CCPD – Crop/breed change and product differentiation; ID – Income diversification; C – Cooperation.

The second challenge is that accurately assessing the effects of agricultural intensity on ecosystem services entails the detailed consideration of several local-specific biogeophysical conditions, socio-ecological processes and complex feedback loops operating with different time-lags. Hence, assessing these processes for the whole of Europe in a comparable way, although possible through the use of large-scale spatially-explicit models (e.g., Maes et al., 2020; Mouchet et al., 2017; Stürck et al., 2018), requires a considerable degree of simplification in terms of both spatial resolution and formal representation of the processes in the models. Such largescale models should only be used for the purpose of mapping major trends and identifying contrasting trajectories across regions (e.g., Felix et al., 2022; Stürck et al., 2018; Verhagen et al., 2018). For an accurate assessment at the local/landscape scale, dedicated models with more detailed data and process representation need to be developed.

With regard to this last point, one must assert that, for the generation of useful narratives to guide action in sustainability governance, it is the quality of the process of production and use of scientific information that matters most, and not necessarily the technical accuracy of the assessment per se (Giampietro et al., 2006; Renner and Giampietro, 2020). Sustainability assessments at the science-policy interface must often deal with "wicked problems", where facts are uncertain, values are in dispute, decisions are urgent, and stakes are high (Kuhmonen, 2018; Saltelli et al., 2020). Consequently, they are inherently fraught with both technical and social incommensurability, leading to considerable and unavoidable uncertainty, both in terms of normative framing and quantitative representation (Giampietro, 2003; Sala et al., 2013). On these grounds, sustainability assessments can greatly benefit from adopting a Post-Normal Science (PNS) approach (Sala et al., 2015; Saltelli et al., 2020). PNS encourages scientists to work closely together with an extended peer community constituted by all those with legitimate stakes or interests, so as to promote mutual learning and safeguard the quality of the process by acknowledging a plurality of perspectives and different types of uncertainty (Funtowicz and Ravetz, 1993; Mayumi and Giampietro, 2006).

In closing, we recommend the proposed approach to be integrally implemented as part of a participatory process involving different groups of stakeholders and experts, for the co-production of knowledge, negotiation of normative dimensions and specification of indicators. Such a process should be conducted in an iterative way, so as to ensure that: i) the chosen system representation is representative of all legitimate sets of perceptions, interests and concerns of different groups of actors; ii) the meaning of the indicators have a shared understanding among actors; and iii) the selected indicator metrics provide a good proxy for defining and assessing their different priorities and targets (Giampietro, 2003; Giampietro et al., 2006). Stakeholders should be involved from the very beginning during the problem formulation phase, because these pre-analytical choices will determine the quality and usefulness of the problem structuring used later on when developing and proposing solutions (Binder et al., 2010; Giampietro et al., 2006; Yegbemey et al., 2014). In addition, it is crucial to ensure that a diverse set of perspectives are included in the process, and that no single interest dominates or constrains the problem-solving process. Power asymmetries, in particular, need to be given special attention, since large organisations may attempt to mainstream implausible narratives on the framing of problems and solutions in order to promote internal agendas, for example, by endorsing "socio-technical imaginaries" that avoid "uncomfortable knowledge" (e.g., Giampietro and Funtowicz, 2020) or manufacturing doubts regarding scientifically well-supported knowledge claims (e.g., Goldberg and Vandenberg, 2021; Kitcher, 2010). The experts leading the process must therefore have an active role in checking the quality and plausibility of the narratives endorsed by different actors and/or generated by the assessment. For this purpose, a diverse set of reflexive analytical tools (e.g., controversy studies, sensitivity auditing, ethics of science for governance) is available and should be applied in order to ensure the saliency, legitimacy and credibility of the different narratives (Saltelli et al., 2020).

The application of the approach through literature review, as illustrated in this article, should therefore be understood only as a first step in supporting researchers during the preparatory phase of an assessment, allowing them to:

- obtain a first comprehensive overview of agricultural intensity and sustainability themes that are potentially relevant, as a basis for mapping out stakeholder groups with legitimate interests and concerns;
- identify available methods and data sources, as the basis for evaluating potential requirements and feasibility of the assessment (e.g., in terms of resources and expertise) and defining priorities;
- identify, a priori, potential blind spots and limitations of the assessment. These include intensity and/or sustainability themes that are potentially relevant but will not be sufficiently covered, due to a lack of resources and data. This, in turn, facilitates transparent communication to the general public, and/or identification of alternative methods (e.g., synthesis studies, participatory methods) that may complement the assessment.

Overall, we consider the approach presented here to be a step forward in defining transparent procedures towards the development of sustainability assessments that can anticipate the feasibility, viability and social desirability of alternative agricultural development pathways. The creation of such transparent information spaces will hopefully stimulate an informed public debate about the operationalisation of SI and increase the quality of deliberation over the sustainability of agriculture and its potential contribution to achieving SDGs.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.08.014.

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Article II: Towards spatial fit in the governance of global commodity flows

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Synthesis

Toward spatial fit in the governance of global commodity flows

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ABSTRACT. Global commodity flows between distally connected social-ecological systems pose important challenges to sustainability governance. These challenges are partly due to difficulties in designing and implementing governance institutions that fit or match the scale of the environmental and social problems generated in such telecoupled systems. We focus on the spatial dimension of governance fit in relation to global commodity flows and telecoupled systems. Specifically, we draw on examples from land use and global agricultural commodity governance to examine two overarching types of governance mismatches: boundary mismatches and resolution mismatches. We argue that one way to address mismatches is through governance rescaling and illustrate this approach with reference to examples of three broad types of governance approaches: trade agreements, due diligence laws, and landscape approaches to supply chain governance. No single governance approach is likely to address all mismatches, highlighting the need to align multiple governance approaches to govern telecoupled systems effectively.

Key Words: *environmental governance; human-environment interactions; scale; spatial mismatch; supply chain; telecoupling*

INTRODUCTION

Local sustainability problems are increasingly shaped by distal actors and processes through global flows of information, people, goods, and services. Demand for commodities such as palm oil, soy, meat, cocoa, and rubber produces negative social and environmental impacts, including deforestation, biodiversity loss, food insecurity, agri-chemical pollution, and consolidation of landholdings, in production regions that are often far removed from sites of consumption (Laroche et al. 2021, Cotta et al. 2022, Roux et al. 2022). Such sustainability problems often transcend traditional political boundaries, which makes it challenging to design governance institutions to fit the scale of the problems. Where governance institutions do not match the scale of the problems they are expected to address, scholars have diagnosed "problems of fit", "mismatches", or "misfits" (Young 2005, Folke et al. 2007, Galaz et al. 2008). The degree of fit may pertain to alignment between a given social-ecological problem and a governance response in spatial, temporal, or functional terms (Cumming et al. 2006, Folke et al. 2007). Issues of governance fit are well researched with regard to regionally bounded or transboundary social-ecological systems such as aquatic or riverine ecosystems (Moss 2012, Bergsten et al. 2014). However, research has not yet systematically explored solutions to spatial mismatches in social-ecological systems connected across long distances, so-called telecoupled systems (Sikor et al. 2013, Munroe et al. 2019, Newig et al. 2020).

Telecoupling denotes long-distance connections between two or more social-ecological systems that are linked through material and non-material flows (Liu et al. 2013, Eakin et al. 2014, Friis et al. 2016). The telecoupling concept supports analysis of how social-ecological changes in one place are related to social-ecological processes elsewhere. Rather than confronting globalization as a diffuse, complex, and all-pervasive phenomenon, a focus on telecoupling helps to delineate and analyze particular connections, place-specific social and environmental impacts, and their (often remote) drivers in a globalizing world (Challies et al. 2014, Friis and Nielsen 2019, Sonderegger et al. 2020).

Governance in telecoupled systems is challenging because the drivers and effects of global flows often lie beyond the reach of national governments, companies, or citizens. Existing sustainability governance initiatives that govern global flows of agricultural and forestry commodities, such as corporate pledges, voluntary sustainability standards, public-private partnerships, and multistakeholder initiatives, are not necessarily effective in driving sustainable supply chains (Garrett et al. 2019, 2021, Grabs et al. 2021, Meemken et al. 2021). Research has attributed the ineffectiveness of governance interventions in part to mismatches between the scale of the governance institution and the scale of the underlying problem (Young 2005).

Here, we explore the problem of spatial fit between governance arrangements and the social-ecological problems they address in relation to land use, as well as global agricultural commodity governance and telecoupled systems more broadly. We focus specifically on the question of spatial fit because telecoupled sustainability problems are inherently related to issues of spatial

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scale. We distinguish two overarching types of spatial mismatches: boundary mismatches and resolution mismatches, building on previous work by Cumming et al. (2006) and Bergsten et al. (2014). Whereas boundary mismatches denote situations in which social-ecological processes transcend governance boundaries, resolution mismatches refer to governance schemes designed at too coarse a spatial scale to effectively address the issue at hand (Bergsten et al. 2014).[1] We present illustrative empirical examples from land and global agricultural commodity governance to elucidate how problems of spatial fit impede the effective governance of land and land-based resources in telecoupled systems. We also examine governance approaches to address this problem. We contend that a better understanding of the types of mismatches that arise in efforts to govern global commodity flows will contribute to identification of leverage points for effective governance interventions in telecoupled systems (Carrasco et al. 2017, Munroe et al. 2019, Newig et al. 2020).

THE PROBLEM OF FIT

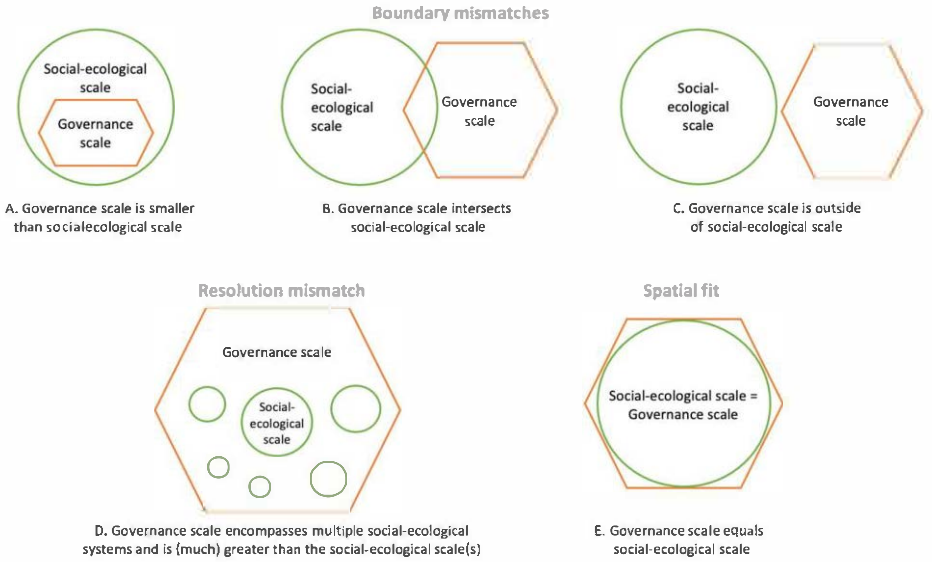
The problem of fit has been widely researched in political science and social-ecological systems literature. Scholars have examined mismatches between the spatial, temporal, and functional scales of governance institutions and the scales of social-ecological processes (Cumming et al. 2006, Folke et al. 2007, Galaz et al. 2008, Ekstrom and Young 2009, Epstein et al. 2015). Here, scale is understood as "the various levels at which a phenomenon occurs in the dimensions of space and time" (Young 2002*a*:26). Because of institutional mismatches, governance responses to environmental threats often struggle to address the full extent of the problem (Ekstrom and Crona 2017). For example, drivers of land-use change operate at multiple levels and spatial scales. International trade, regional development policies, national property rights regimes, and local people's agricultural practices are among the many factors that may lead to land conversion (Geist and Lambin 2002). However, governance mechanisms typically target a single level (e.g., national forestry laws), and thus do not provide adequate solutions to the challenge of governing wider resource systems (Nagendra and Ostrom 2012). Governance arrangements that only partially cover the resource or ecosystem in question have built-in limitations that impede their ability to fulfill their goals (Young 2005).

Various possible configurations of spatial mismatches exist (Fig. 1). The governance scale may be smaller than the social-ecological system scale (Fig. 1A). For example, a municipality may not be able to effectively address air pollution, which is caused by local factories but dispersed beyond municipal boundaries. Governance at larger scales, such as national regulations, may solve the problem (upscaling of governance). Similarly, the governance scale may only partially cover the social-ecological scale (Fig. 1B), as is often the case, for example, with governance of transboundary rivers. In such situations, upscaling may be more difficult in the absence of an authority at a higher governing level. Moreover, governance institutions and actors may have no jurisdiction at all over the social-ecological scale of an identified problem (Fig. 1C), such as in the case of a country lacking the authority to regulate illegal logging by a company domiciled in the country but operating in a neighboring country. Lastly, the governance scale may be greater than the social-ecological scale (Fig. 1D). In such cases, regulation at a (much) larger scale than that of the ecological problem may lack the regulatory specificity to "come to terms with local variations in biogeophysical conditions and [lack] sensitivity to both the knowledge and the rights and interests of local stakeholders" (Young 2002*b*:283; see also Ostrom 1990). For example, much of European Union legislation has been criticized for being too insensitive to local contexts, despite the EU's principle of subsidiarity (Article 5 Treaty on European Union), which demands that decisions should be taken at the most appropriate level of governance, and that the EU should only take action when national, regional, or local governments are unable to achieve a particular objective. The EU Water Framework Directive provides an example of governance that seeks to avoid resolution mismatches. It requires member states to develop River Basin Management Plans to guide local and context-specific implementation (Jager et al. 2016). An institutional fit emerges if the governance scale equals the social-ecological scale (Fig. 1E), as in the case of the global agreements reached in the Montreal Protocol on Substances that Deplete the Ozone Layer to address a global problem (Epstein et al. 2014).

Fundamentally, the problem of fit concerns the question of how to scale or rescale governance arrangements so that they have the best possible institutional fit with the targeted social-ecological dynamics. Establishing the most appropriate fit requires a trade-off between the advantages of better coordination at higher scales, which may reduce the risk of overlooking spatial externalities, and the risk of lacking context sensitivity and legitimacy among local actors, impeding effective implementation (Newig and Moss 2017). Importantly, problems do not occur at a single scale that is objectively given, but different actors perceive and frame problems at different scales and levels (Padt et al. 2014). For example, if state actors aim to meet forest restoration commitments made under international agreements and frame the problem solely at an ecological scale, a national afforestation program fits with the objective of forest restoration for carbon storage. However, if the problem is framed at a social-ecological scale, a single homogeneous afforestation program may suffer from a resolution mismatch and fail to address context-specific challenges related to rural livelihoods (Wiegant et al. 2020, Coleman et al. 2021). Thus, evaluations of fit depend upon how a problem is framed and by whom (Epstein et al. 2015). What is perceived as the "optimal scale" may vary among actors, and the scale at which they define a problem will influence their preferences for governance rescaling. For example, political and societal actors may strategically frame certain problems at the global scale if they perceive national governments as a possible hindrance to solving the problem, or if they want to avoid assuming responsibility and implementing domestic measures (Gupta 2014).

Here, we build on the concept of institutional fit, which is based on the underlying normative assumption that institutional scale can be optimized to avoid spatial externalities (Moss and Newig 2010). Thus, we focus on how individual institutions face this problem of fit. Nevertheless, we recognize that governance always involves the interplay of different institutions. Analysis of institutional fit is closely linked to the analysis of institutional interplay because social-ecological problems are typically governed by various institutions at different spatial scales (Young 2002*a*). Although no institution operates in a vacuum, it can be useful to assess the spatial fit of a specific institution in isolation from the broader institutional landscape. This approach simplifies

Fig. 1. Scale (mis-)matches between social-ecological (green) and governance (orange) scales. (A–C) Boundary mismatches. The institutional boundaries do not match with the spatial boundaries of the social-ecological problem, creating spatial spillover effects. (D) Resolution mismatch. The governance institution does not fit the specifics of the (local) social-ecological context that is to be addressed by governance and hence lacks sufficient spatial specificity. A single governance institution typically addresses a class of social-ecological problems that occurs in multiple distinct localities that have specific contextual features, to which a single governance institution cannot necessarily be adjusted. (E) Spatial fit. Illustration inspired by Newig et al. (2013:13).



the analysis and does not consider all interdependencies, but it enhances analytical tractability and makes it easier to identify governance weaknesses and gaps (Young 2005). The analysis of institutional mismatches can be complemented with considerations of how to create linkages and facilitate interactions among various institutions. We return to considerations of the relation between institutional fit and interplay below.

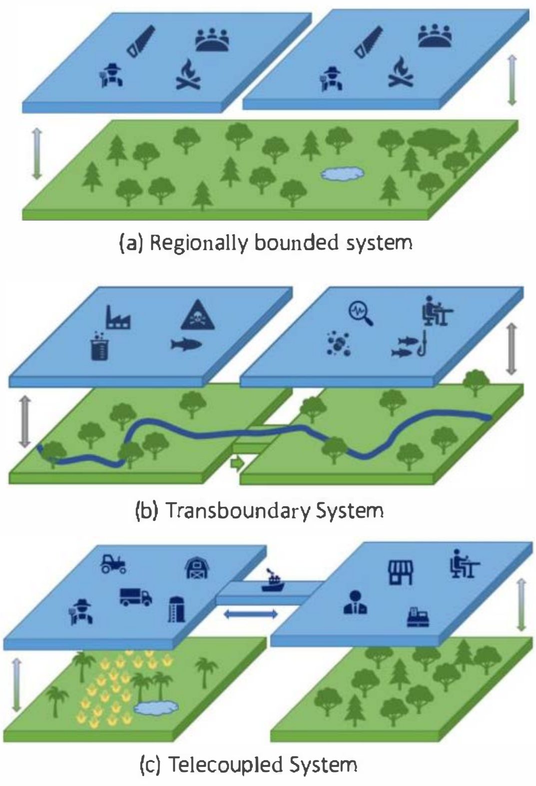
THE PROBLEM OF SPATIAL FIT IN TELECOUPLED SYSTEMS

Research on institutional fit has primarily focused on cases of natural resources in specific social-ecological systems. Studies have been conducted on forest governance (Shkaruba and Kireyeu 2013, Bodin et al. 2014, Melnykovych et al. 2018), water governance (Lebel et al. 2005, 2013, Moss 2012, Enqvist et al. 2020), and land and wildlife management (Bergsten et al. 2014, Dressel et al. 2018). Most research has focused on mismatches between local, regional, and national governance institutions and the social-ecological systems they target, but a small and growing pool of literature investigates transboundary and larger scale social-ecological problems such as depletion of the ozone layer or pollution of international watersheds (Cox et al. 2014). Challies et al. (2014) observe that social-ecological systems research itself has mostly examined small, tightly coupled systems, rather than connections and interdependencies that exist between multiple social-ecological systems linked through global production networks and supply chains (Nyström et al. 2019). Research on telecoupling is increasingly addressing this research gap by investigating the causes, drivers, and implications of globally linked social-ecological systems. Telecoupling research has referred to the problem of mismatches, but the definition and application of the concept in the context of telecoupling remains limited (Oberlack et al. 2018, Munroe et al. 2019, Zaehringer et al. 2019, Newig et al. 2020). The important question of how to align the scale of governance with the scale of the social-ecological problem at hand remains largely unaddressed in research on governing telecoupled social-ecological systems.

Telecoupling is one distinct ideal-typical configuration of interdependent social-ecological systems (Fig. 2). Telecoupled systems arise when the activities of actors in one system affect a social-ecological system elsewhere (e.g., through international trade or the displacement of extractive activities from one place to another), thereby creating social-ecological interdependencies. Consequently, feedbacks can develop, for example, when actors in one location become aware of the displaced effects of their actions and seek to mitigate them through measures such as increased conservation funding.

Telecoupled systems are characterized by geographical distance between the place where the social or environmental impacts occur and the places where underlying causes are found. The geographical distance is often associated with social and institutional distances between the socioeconomic systems (Eakin et al. 2014, Niewöhner et al. 2016, Friis and Nielsen 2017) because they tend to be governed by different, functionally independent institutional arrangements, social networks, and actors (Eakin et al. 2017). Even when distant actors are willing to work together, transaction costs of cooperating on sustainability issues are often much higher than in local or transboundary settings (Newig et al. 2020). Geographical, social, and institutional distances thus hinder the creation of appropriately scaled governance institutions in telecoupled systems in at least four ways.

Fig. 2. Ideal types of interconnected social-ecological systems and their interdependencies. Systems comprise socioeconomic building blocks (blue), ecological building blocks (green), and their interdependencies (arrows). (A) In a regionally bounded system, two socioeconomic systems share the same ecological resource base; e.g., two communities harvest wood from the same forest. (B) In a transboundary system, two socioeconomic systems rely on resources or ecosystems that are ecologically connected; e.g., pollution of a river by an upstream riparian country may affect fish populations in a downstream riparian country. (C) In telecoupled systems, the ecological systems are geographically separate but are connected through social-ecological processes such as trade in agricultural commodities.



First, the absence of manifest ecological feedbacks between telecoupled systems obscures the remote causes and effects of certain decisions and actions. In many locally bounded or closely neighboring social-ecological systems, the activities of one group of resource users will have direct effects on other users (Lebel et al. 2005, Bergsten et al. 2014, Kininmonth et al. 2015). With transboundary water resources, for example, withdrawals in one place affect downstream availability. In telecoupled systems, however, there is usually no such direct ecological feedback. For example, tropical ecosystem degradation driven by commodity production for export to European markets causes biodiversity loss in producing regions or carbon emissions, but does not directly affect European consumers in the short term. Where feedbacks are delayed or indirect, it is also difficult to attribute specific social-ecological effects to particular activities (Carlson et al. 2018). Consequently, the actors driving telecoupled interactions do not necessarily experience the negative effects of their actions or recognize the connections between past actions and subsequent negative effects (Newig et al. 2020). They may therefore have very little incentive to formulate or adapt governance responses.

Second, as a result of the above situation, recognition of and concern about specific problems may depend on social or political actors highlighting causal linkages between certain actions and distant outcomes. "Problem-brokers" or "political entrepreneurs" can play important roles in framing and problematizing unsustainable connections between telecoupled systems (Bastos Lima et al. 2019, Meyfroidt et al. 2022). Once distant ecological or social conditions attract sufficient public attention and concern, a policy window opens wherein various governance interventions may become possible (Kingdon 1984, Eakin et al. 2017). Improved transparency, through the collection and dissemination of information on flows and impacts, can enable or instigate governance responses to telecoupled issues (Gardner et al. 2019). For instance, increasing media attention on environmental issues such as deforestation has put pressure on the EU to address soybean production in the Amazon region (Mempel and Corbera 2021). Several interventions have emerged to tackle deforestation embedded in international trade and to reduce "imported deforestation" from EU consumption (Bager et al. 2021).

Third, governance mismatches arise when governance responses misdiagnose a problem or neglect its wider drivers. Interventions that target only the direct ecological effects of an activity risk merely displacing it to other social-ecological systems. For example, European demand for soy is associated with negative ecological impacts such as deforestation in producer countries (Pendrill et al. 2019, Schilling-Vacaflor et al. 2021). Addressing tropical deforestation at the scale of a single region such as the Amazon is unlikely to be effective because demand for forest-risk commodities will persist. Therefore, governance interventions such as the Brazilian Soy Moratorium, which targets the Amazon specifically, have displaced deforestation to other areas such as the Cerrado region (Dou et al. 2018).

Fourth, the places and governance institutions implicated in telecoupled systems may have very little history of prior collaboration (Newig et al. 2020). The social and institutional distance between telecoupled systems may mean that separate policies, actors, and networks govern largely independently. In the absence of joint institutional structures, governing telecoupled systems is challenging because governance actors face issues that extend beyond their jurisdiction. For example, consumption in the EU has social-ecological effects beyond EU borders (Kastner et al. 2015, Dorninger et al. 2021, Roux et al. 2021). However, the EU's ability to govern these issues has clear limitations given the national sovereignty of external countries and World Trade Organization rules.

DIFFERENT TYPES OF MISMATCHES IN TELECOUPLED SYSTEMS

We apply the concepts of boundary and resolution mismatches to telecoupled systems. We identify the underlying governance problem associated with each type of mismatch, outline two particular mechanisms of boundary mismatches and illustrate with examples from both public and private governance perspectives (Table 1). Our distinction between ideal-typical configurations of mismatches helps in elaborating how the scale of governance institutions often does not align with the scale of social-ecological problems.[2]

Boundary mismatches in telecoupled systems

Boundary mismatches arise in telecoupled systems when the spatial reach of governance structures is such that these structures do not internalize existing social-ecological externalities of activities (i.e., spillovers; Fig. 3A) or when public policies or transnational economic activities produce new externalities (i.e., leakages; Fig. 3B). Spillovers describe events or developments that are not targeted by a given governance intervention, whereas leakages are a form of spillover caused by a governance intervention (Meyfroidt et al. 2020).

Spillover

In case of spillovers (Fig. 3A), part of the problem remains unaddressed because it lies outside the domain of the governance institution. The omitted part of the problem is referred to as a spillover, which is broadly understood as an indirect effect of an activity or intervention (e.g., policy, program, or new technology) that occurs outside the targeted area (Meyfroidt et al. 2020). Spillovers emerge because governance actors may not be aware of the full scale of the social-ecological problem, may be uninterested in or unable to govern what happens beyond their jurisdictional boundaries, or may intentionally neglect parts of the problem (Bastos Lima et al. 2019). For example, voluntary sustainability standards often focus on reducing harmful on-farm effects at sites of production but tend to neglect off-farm effects such as reduced downstream water availability or air pollution from pesticide use (Zaehringer et al. 2018, Parra-Paitan and Verburg 2022, Sonderegger et al. 2022). Spillovers can also cascade to further social-ecological systems (as indicated in Fig. 3A) and have cumulative effects, which makes it difficult to identify causal connections (Busck-Lumholt et al 2022*a*).

The transnational operations of companies make it challenging to achieve institutional fit and to internalize the extra-jurisdictional social and environmental effects of global supply chains. Because multinational enterprises operate beyond the jurisdictional reach of individual states, the externalities of their activities are often not addressed by existing governance institutions. These actors are not accountable to any single authority that matches their scope of operation (Kobrin 2009).

Private actors may encounter boundary mismatches in their efforts to govern supply chains for two reasons. First, individual companies may lack oversight and influence over some or all of their suppliers and therefore lack the ability to control the environmental and socioeconomic effects of production. For example, approximately one-quarter of the solid wood furniture that IKEA sells is manufactured in Chinese factories that source their timber from other countries, in particular Russia (Newell and Simeone 2014). IKEA attempted to control the timber sourcing of its Chinese subcontractors to "green" its supply chain but was unsuccessful because of the geographical distance to upstream activities, the large number of intermediaries between timber extraction and retail, and an inability to trace timber to a specific logging permit (Goldstein and Newell 2020). Additionally, supply chain configurations change over time (dos Reis et al. 2020). China has long depended on Russian wood for the manufacture of finished wood products for export to the United States, but the specific companies within these supply chains change regularly (Goldstein and Newell 2020). Even where large, powerful retailers dictate prices and quality standards to their suppliers, their ability to control sustainability along the value chain is often limited because of the mismatch between their governance reach and the scale of the social-ecological problem. Companies are often not able to monitor their indirect suppliers, which makes it difficult to implement chain-wide sustainability policies (zu Ermgassen et al. 2022).

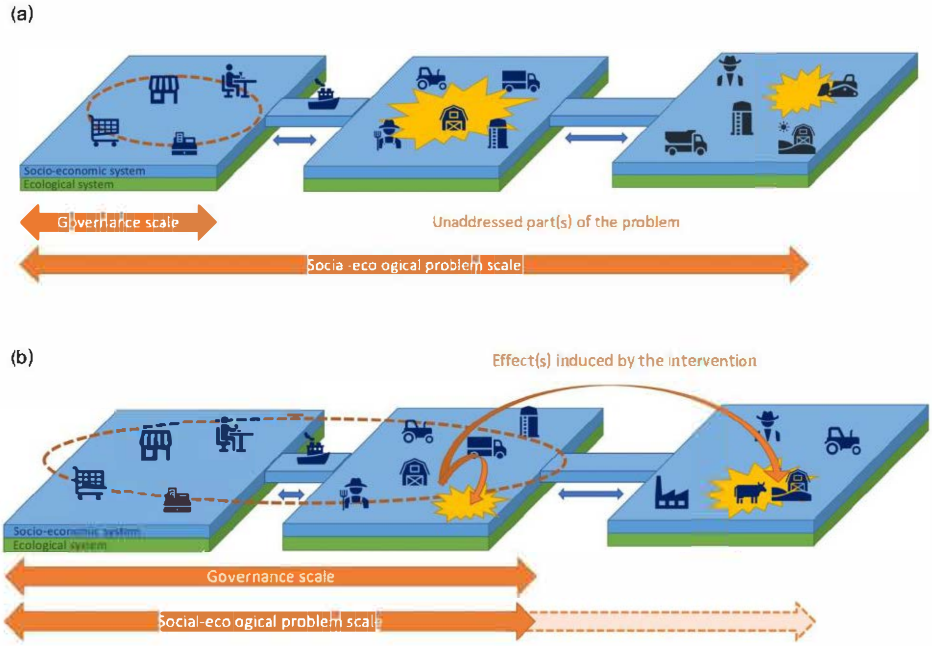
Second, companies may govern particular segments of their supply chain but neglect others, which constitutes a boundary mismatch if the goal is to create sustainable supply chains that encompass the full value chain. For example, textile certifications generally focus on either the upstream end of the supply chain (i.e., organic and fair cotton production) or the midstream section (i.e., working conditions of garment workers; Partzsch 2020), but seldom cover all segments of the supply chain.

Leakage

A leakage may emerge when a governance intervention induces externalities (Fig. 3B). The governance intervention produces effects that contradict its objectives and reduce the overall benefit of the interventions, which constitutes a leakage effect (Meyfroidt et al. 2018, Bastos Lima et al. 2019). For example, the EU's Renewable Energy Directive created additional demand for biofuel crops produced outside of the EU and thereby fuelled land-use change and deforestation in tropical countries, counteracting the goal of reducing greenhouse gas emissions (Bastos Lima 2021). This process has also been described as "governance inducing telecoupling" (Newig et al. 2019), i.e., situations in which governance initiatives themselves create new distal interactions with positive or negative outcomes. Recognition of the negative distal effects led to revision of the Renewable Energy Directive to mitigate indirect land-use change (Bastos Lima 2021). In other instances, the leakage effect does not occur across a great distance but can be in proximity to the target area. For instance, if a forest moratorium prohibits deforestation within designated areas, the activity may simply shift to nearby areas not covered by the moratorium (Meyfroidt et al. 2010, Leijten et al. 2021).

Just like public governance, private governance can have spillover effects and leakages. For instance, if private conservation actors focus their efforts on specific regions such as the Brazilian Amazon, that leaves other regions such as the Cerrado and Gran Chaco comparatively less well protected, and land conversion

Fig. 3. Boundary mismatches. Governance institutions neglect social-ecological problems that transcend established jurisdictional boundaries due to spillovers (A) or leakages (B).



may be displaced to those regions (Soterroni et al. 2019, Qin et al. 2022). In short, leakage occurs when the side effects of an intervention escape the scope of governance.

Resolution mismatches in telecoupled systems

Resolution mismatches represent a second problem of governance lit in telecoupled systems (Fig. 4). Because international or transnational governance institutions usually aim to address a social-ecological problem that occurs in more than one place, they are not specific to the social and ecological attributes of a particular social-ecological system or a particular telecoupling. If governance occurs at too coarse a scale, meaning that governance instruments are not context sensitive or flow specific, they are unlikely to be successful because "one-size-lits-all" panaceas do not exist (Ostrom et al. 2007, Meyfroidt et al. 2022).

For example, international governance schemes such as Multilateral Environmental Agreements tend to be too general to govern specific telecoupled systems because international conventions, agreements, and commitments typically involve a large number of signatories, have a general thematic scope, and are not specific to any particular flow.[3] Of approximately 250 Multilateral Environmental Agreements worldwide, only 15 explicitly include trade-related provisions for environmental protection (World Trade Organization 2021). International governance schemes cover a large spatial scale and require a broad institutional outlook that can be implemented in heterogeneous national and local contexts. Because most international institutions are not supranational, meaning that they do not have authority beyond that of their respective members, they rely on lower-level institutions for implementation, which, however, have limited abilities to govern the causes or effects of cross-border flows beyond their jurisdictional boundaries. If the implementation pathway is not defined and lower-level institutions have neither the capacity nor the experience to implement higher-level governance objectives, a spatial scale challenge emerges (Wiegant et al. 2020). Global environmental governance is often directed toward reaching global targets (e.g., Paris Agreement, Aichi Biodiversity Targets, Bonn Challenge). However, target-based governance has been criticized for the gap between international policy and national implementation, the missing linkages between national governments and on-the-ground actions, and the unclear definitions of some wording of the targets (Hagerman et al. 2021, Perino et al. 2022).

In the context of private governance, supply chain actors may set broad, blanket-coverage sustainability goals that are meant to apply across entire supply chains but are, for that reason, ambiguously defined, limited in scope, and poorly operationalized in terms of concrete and measurable targets. For example, in a sample of 513 companies in the coffee sector, only one-third reported tangible commitments to sustainability, whereas the remaining companies reported no or vague commitments (Bager and Lambin 2020). Similarly, companies may adopt zero-deforestation commitments without setting clear implementation goals, mechanisms, or deadlines, which impedes effective implementation across the contexts in which they operate (Garrett et al. 2019).

Table 1. Boundary and resolution mismatches in the governance of telecoupled social-ecological systems.

	Boundary mismatch		Resolution mismatch
Definition[†]	Governance institutions neglect social-ecological problems that transcend established administrative or jurisdictional boundaries		Governance institutions have too coarse a spatial resolution than is suitable to address the social-ecological problems at hand
Underlying problem	Lack of governance extent		Lack of governance precision
Mechanism	Spillover	Leakage	Panacea trap
Description	Governance institutions do not govern a social-ecological problem that expands beyond their administrative or jurisdictional boundaries	Governance institutions address a social-ecological problem but create leakage(s), i.e., counterproductive effects outside the targeted area or domain of the intervention	Governance institutions are not specific enough to be effectively implemented and enforced
Example from a public policy perspective[‡]	European countries have not (yet) implemented specific public policies to mitigate the deforestation effects of their demand for soy in remote jurisdictions[§]	A forest moratorium shifts deforestation to neighboring areas or other countries, producing negative externalities in distant jurisdictions	A Multilateral Environmental Agreement that is too broad in scope to govern particular telecoupled flows
Example from a private governance perspective	A Voluntary Sustainability Standard focuses on reducing harmful on-farm impacts at sites of production but neglects sustainability issues outside the farm such as air pollution from pesticide use	Supply chain actors implement zero-deforestation policies that target only one region, allowing actors in other regions or neighboring countries to deforest	Supply chain actors set broad sustainability goals that are insufficiently operationalized and lack specific and measurable targets, unambiguous definitions, and exact coverage

[†]Adapted from Bergsten et al. (2014).
[‡]We present the different types of mismatches from both public policy and private governance perspectives because their analytical focus differs. From a public policy perspective, the focus is on the jurisdictional scale, defined as clearly bounded political units (e.g., towns, provinces, states, or countries; Cash et al. 2006). In contrast, the private governance perspective puts more emphasis on the scale of the supply chain or associated flows.
[§]The newly adopted EU Regulation on deforestation-free supply chains addresses this mismatch (European Commission 2022). It is expected to enter into force in summer 2023. Once it is in force, operators and traders will have 18 months to implement the new rules.

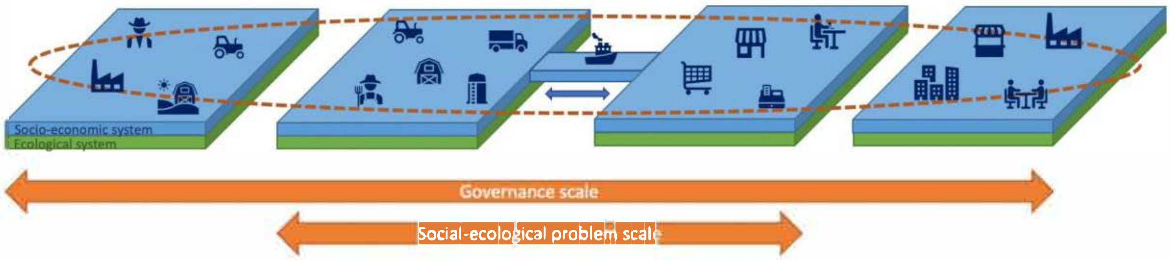
As a result of resolution mismatches, new kinds of mismatches may emerge when governing institutions do not reflect the values, interests, and beliefs of different social groups. What Epstein et al. (2015) have termed "social mismatches" points to the spatial scalar challenge of matching governance objectives and rules with social customs and patterns of resource use, stakeholder expectations and needs, and social organization scales (Epstein et al. 2015). In telecoupled systems, international governance based on global goals carries a clear risk of diverging from issues that are seen as most important by local stakeholders. Global initiatives such as the Kimberley Process, for example, promote transparency in supply chains, but in so doing, they risk favoring global ideals (e.g., of traceability and accountability) over the day-to-day needs and concerns of local communities (Pedersen et al. 2021*a*). Research on gold mining in Tanzania, for instance, found that a centrally imposed transparency initiative had not addressed inequalities, informal structures, and power asymmetries in the mining sector (Pedersen et al. 2021*b*). Likewise, conservation projects that are governed by external actors (such as states, international nongovernmental organizations, or private firms) tend to subordinate local institutions, customary practices, and traditional ecological knowledge, resulting in relatively ineffective conservation management (Dawson et al. 2021). International conservation initiatives may overlook social and political complexities in local systems and create unintended and undesirable effects, including restricted access to land and natural resources and the erosion of customary natural resource governance institutions (Persson and Mertz 2019, Persson et al. 2021). If local people are merely seen as recipients of services and are not involved in the design of sustainability interventions, a mismatch between local goals and strategies and those of the wider project can emerge. In the case of a World Bank conservation project in Argentina, project concepts and ideas were decided by external actors, rather than in partnership with local beneficiaries (Busck-Lumholt et al. 2022*b*). Sustainability issues prioritized at the global scale may not match with local people's understanding of and aspirations for sustainability.

Self-governance and local rule development have been found to be highly important for effective natural resource management (Ostrom 1990). Otherwise, there is a high risk that international or transnational governance schemes are insufficiently adapted to local contexts. If governance actors perceive that transnational institutions do not fit the local contexts (i.e., social mismatch as result of a resolution mismatch), they may create their own institutions. This situation occurred with the establishment of the Icelandic Responsible Fisheries certification program as an alternative to the transnational Marine Stewardship Council certification scheme (Foley 2017), and with the introduction of Indonesian and Malaysian Sustainable Palm Oil schemes as alternatives to the Roundtable on Sustainable Palm Oil (Higgins and Richards 2019).

ADDRESSING MISMATCHES IN TELECOUPLED SYSTEMS

These examples suggest that global commodity flows, through boundary and resolution mismatches, pose multiple environmental governance challenges that are difficult to address through territorial or global governance approaches. Against this background, both public and private actors have attempted to rescale governance to account for social-ecological interactions

Fig. 4. Resolution mismatches. Governance institutions have a coarser scale than is suitable to address the social-ecological problems they target.



across long distances and between jurisdictions. With respect to global governance, governance rescaling has been defined as "a shift in the locus, agency, and scope of global [...] politics and governance across scales" (Andonova and Mitchell 2010:257). Scaling up governance to make it more comprehensive in terms of target area, actors, or supply chain segments can limit the risk of boundary mismatches. In contrast, scaling down governance might enhance the context sensitivity of interventions and the participation of local stakeholders, thus correcting resolution mismatches. Additionally, creating new governance scales can be another strategy to avoid mismatches. In telecoupled systems, such governance institutions comprise due diligence laws, as elucidated below. We next present three illustrative examples of public, private, and hybrid governance forms to illustrate the opportunities and challenges involved in addressing both boundary and resolution mismatches.

Social and environmental provisions in trade agreements

The inclusion of binding, measurable, carefully monitored, and sanctionable social and environmental provisions in preferential or regional trade agreements presents a potential instrument to govern trade-related environmental impacts between specific countries or regions (Kehoe et al. 2020). Recently, researchers have advocated shifting focus on the relation between trade and the environment away from merely mitigating the negative impacts of trade, and toward focusing on how to harness the positive environmental effects of trade through, for example, the use of so-called "trade-and-environment agreements" (Roux et al. 2021; https://ieep.eu/news/a-cup-of-trade-and-environment-agreement-tea/). In theory, environmental provisions in trade agreements can oblige parties to uphold environmental law and implement "Multilateral Environmental Agreements"; increase cooperation, transparency, and participation in environmental matters; and trigger the uptake of voluntary sustainability standards and public regulations targeted at sustainability issues of a specific sector or product. However, empirical evidence of the actual environmental effects of environmental provisions in trade agreements is scarce and inconclusive (Berger et al. 2020).

Although trade agreements do address specific flows at the scale of telecoupled relations, they pose a risk of leakage because trade flows may shift geographically (i.e., trade diversion), and regulated commodities may be replaced by less regulated or unregulated commodities within supply chains (i.e., substitution effect). For example, the U.S.-Peru trade agreement includes a binding Forest Annex, which details measures to strengthen forest governance in Peru, including the establishment of chain-of-custody systems to verify the legality of timber exports. However, because the Forest Annex is strongly focused on protecting CITES-listed timber species, one risk is that it increases exports of species not listed in CITES. It could also prompt U.S. importers to switch to other, less regulated markets (Del Gatto et al. 2009). Governance institutions that target specific geographic areas or commodities risk creating boundary mismatches. This situation suggests that trade agreements may be more effective at reducing leakage effects at regional scales when they contain binding, measurable, and enforceable sustainability chapters, and they involve regional blocs rather than individual countries, and commodity groups rather than single commodities. However, the risk of resolution mismatches increases when the spatial scale of trade agreements increases.

Trade agreements can suffer from resolution mismatches. For example, Berger et al. (2020) reviewed 48 preferential trade agreements of five emerging economies and found that three-quarters of the agreements make reference to general environmental goals in their preamble or other chapters. However, these provisions are not of substantive nature, meaning that they do not imply any substantive rights or obligations in environmental matters to the parties. Additionally, some countries restate their commitment to ratify or implement Multilateral Environmental Agreements in their trade agreements, thus, only restating the pledges already made elsewhere. If countries only make commitments to general environmental goals and international conventions without defining concrete actions in their trade agreements, they are unlikely to address the specific social and ecological problems of telecoupling in particular social-ecological systems.

Moreover, if the needs and priorities of local communities are overlooked or deprioritized, social mismatches may arise. Failure to recognize the economic, social, and environmental concerns of affected communities can also induce a boundary mismatch. For example, a trade ban may prove ineffective if it does not recognize the economic concerns of local communities, who may derive little economic benefit from the ban, and hence have little incentive for conservation or sustainable resource use (Abensperg-Traun 2009). Consequently, the resource may be sold illegally or into alternative markets, creating leakage effects that limit the effectiveness of the trade ban. For instance, Busch et al. (2022) estimated that a European ban on importing high-deforestation palm oil from Indonesia would have only minor effects on deforestation because, among other reasons, non-participating countries would absorb the high-deforestation palm oil. More research is needed on how to avoid mismatches when designing trade agreements and trade bans.

Due diligence obligations and laws

The proliferation of due diligence policies shows that public sector actors increasingly govern social and environmental conduct beyond their own borders. Due diligence policies are a clear example of "rescaling" or "territorial extension", whereby states or groups of states extend their regulatory influence to actions abroad (Scott 2020). Although due diligence laws are implemented within formal administrative boundaries on a jurisdictional scale, they govern extra-jurisdictional processes by obliging transnational companies to monitor their supply chains and to rectify unsustainable impacts. Due diligence policies tend to be applied at scales applicable to telecoupled systems because they address flows that extend beyond jurisdictional boundaries.

Due diligence requirements often apply to specific commodities, as in the case of the EU Timber Regulation, which prohibits the sale of illegally harvested wood on the EU market, and the EU Renewable Energy Directive, under which member states can count biofuels toward the attainment of their renewable energy targets only if the biofuel production complies with certain sustainability criteria (European Union 2018), irrespective of whether the biofuel crops are produced inside or outside the EU (Scott 2020). Additionally, the EU adopted a Regulation on deforestation-free supply chains in December 2022, which prohibits the placing of palm oil, soy, wood, cattle, cocoa, coffee, rubber, and some derived products on the EU market if these commodities are linked to deforestation and forest degradation or if they are non-compliant with all relevant applicable laws in force in the country of production (European Commission 2022). These sector-specific due diligence policies use conditional market access as a mechanism to secure foreign producers' compliance with EU rules. More recently developed, economy-wide, mandatory due diligence laws, at the national and European levels, rely on another governance mechanism, namely self-reporting and public scrutiny. The French Duty of Vigilance Law, for example, requires companies to assess and report the risks of infringing environmental and human rights in their supply chains, as well as measures to mitigate such risks. If preventable human rights violations or environmental damages occur, the company can be held liable and can be required to remedy the harm (Schilling-Vacaflor 2021). Additionally, the European Commission proposed a Directive on sustainable corporate governance that covers human rights and environmental due diligence (Schilling-Vacaflor and Lenschow 2023). In sum, due diligence laws attempt to alleviate the boundary mismatch that occurs because importing countries, in principle, have no jurisdiction over producing countries, where sustainability problems appear.

However, due diligence policies may suffer from resolution mismatches because they do not target any particular locality, but rather general social-environmental problems, irrespective of their local manifestation. This situation can lead to social mismatches. The EU Timber Regulation, for example, demands that timber is sourced legally according to the laws of the producer country. However, such policies that are reliant on local laws risk endorsing certification systems that neglect the rights of certain local communities (Bartley 2014) and work against sustainability by incentivizing a regulatory "race to the bottom" among exporting countries (dos Reis et al. 2021). Furthermore, if mandatory due diligence laws require companies to report on risk mitigation in their supply chains, companies may focus their reporting on issues that are not key priorities for local stakeholders. For example, under the French Duty of Vigilance Law, companies have focused on environmental issues such as deforestation in the soy and beef supply chains while neglecting other issues such as biodiversity loss, pesticide use, water scarcity, and water pollution. The companies prioritize labor rights, whereas the rights to health, land, water, and food may be more important for local stakeholders (Schilling-Vacaflor 2021).

Landscape or jurisdictional approaches to supply chain governance

Landscape approaches aim to reconcile competing social, economic, and environmental interests and objectives at the landscape scale. Landscape approaches have been widely employed in international conservation projects and are now also increasingly taken up in sustainable supply chain management (Sayer et al. 2013, Boshoven et al. 2021). They are based on multistakeholder collaboration (e.g., public authorities, producers, companies, civil society organizations), which sets them apart from purely public jurisdictional governance approaches that do not seek to involve all affected stakeholders. These relatively recent governance approaches rest on the premise that the involvement of public actors allows for the implementation and enforcement of mandatory requirements for production practices, provided that enforcement capacities exist (Bager 2021). Public actors have regulatory authority over the area covered, "allowing for better monitoring and enforcement as well as addressing the problem of institutional mismatch" (von Essen and Lambin 2021:6–7). A jurisdictional approach is a type of landscape approach that uses formal administrative boundaries to define the scope of action and involvement of stakeholders (Denier et al. 2015).

Landscape and jurisdictional approaches aim to avoid the boundary mismatches that commonly affect public and private governance initiatives that focus exclusively at farm or supply-chain scales. This narrow focus can create "islands of good practice" while surrounding areas continue with business as usual (UNDP 2019:12). Many of the social-ecological problems that sustainability initiatives such as voluntary sustainability standards target manifest in the wider landscape, leading to mismatches between the scale of the intervention and the scale of the sustainability challenges being addressed (Sonderegger et al. 2022). For example, where companies seek to reduce commodity-driven deforestation by certifying some of their own or their suppliers' farms or plantations, deforestation may shift to non-certified areas (Heilmayr et al. 2020). Jurisdictional and landscape approaches are assumed to reduce the risk of leakages (and thus boundary mismatches) because they target entire jurisdictions or landscapes rather than a selected smaller area. In terms of certification and standard-setting, landscape and jurisdictional approaches have been introduced to upscale governance to reduce the risk that commodity sourcing produces ungoverned impacts beyond the production area or unit (e.g., farms). Sustainable cocoa initiatives, for example, are evolving in their focus from the farm level to sector, landscape, and jurisdictional levels (Carodenuto 2019, Parra-Paitan et al. 2022, 2023). Empirical evidence on the effectiveness of landscape and jurisdictional approaches is scant, however, given their recent emergence (Bager 2021, von Essen and Lambin 2021).

Jurisdictional and landscape-based certification and sourcing also have limitations. Governance at the landscape level remains limited to a certain regionally confined scale and may not address all potentially relevant telecoupled dynamics such as migrant worker flows or illicit financial flows (Sonderegger et al. 2022). Additionally, the risk of leakage persists because neighboring jurisdictions may have weaker environmental protections (von Essen and Lambin 2021). Non-compliant production may shift to neighboring places with fewer restrictions (Meyfroidt et al. 2018), and commodities from non-compliant neighbors might be laundered into the more tightly regulated jurisdiction (Gibbs et al. 2016, Boshoven et al. 2021).

Institutional interplay

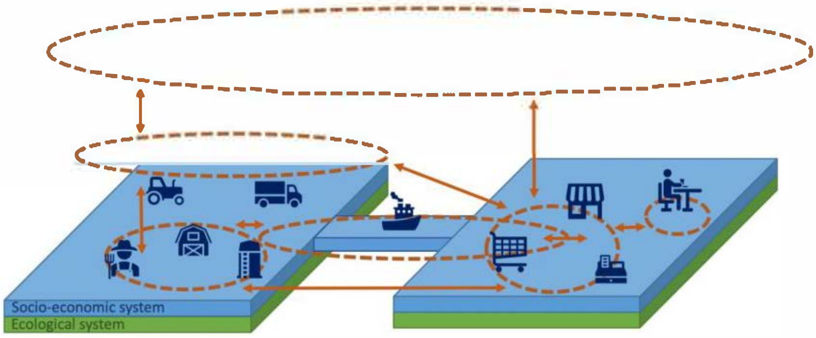
Although we focus on how specific institutions can define and address what they conceive as mismatches, in practice, telecoupled systems are typically governed by several institutions, which interact horizontally at the same level of social organization or vertically across levels (Fig. 5). Institutions influence the decision-making, commitments, behavior, and effects of one another (Oberthür and Gehring 2006). Institutional interplay is based either on functional linkages that occur when developments in one issue area unavoidably affect another issue area, such as between institutions on agricultural production and land use, or it is based on political linkages that arise when actors recognize interdependencies and deliberately forge institutional interactions (Young 2005). For example, the EU's Forest Law Enforcement Governance and Trade (FLEGT) initiative interacts with private certification schemes and public legal timber regulations in partner countries (Overdevest and Zeitlin 2014). FLEGT promotes better enforcement of forest law and the establishment of export licencing systems in partner countries to identify, monitor, and export legally harvested timber products destined for EU markets. Additionally, the FLEGT initiative, adopted in 2003, encouraged U.S. environmental activists to advocate for an extension of the U.S. *Lacey Act* from fish and wildlife to plants, leading to amendment of the *Lacey Act* in 2008. This example highlights how institutional interactions can lead to the convergence of separate national or regional governance regimes. The convergence between FLEGT and the U.S. *Lacey Act* ensured that illegally harvested timber is not simply diverted from one market to another (Overdevest and Zeitlin 2014).

Creating effective collaborative ties between institutions has been repeatedly proposed as a solution to rectify mismatches (Galaz et al. 2008, Bodin et al. 2017, Enqvist et al 2020). Bergsten et al. (2014:1) argue that "boundary mismatches are impossible to resolve if the focal ecological processes are not contained within the spatial jurisdiction of either a single high-level actor responsible for the whole area or by several lower level actors who collaborate" and thus jointly build a comprehensive governance system at a larger scale. This idea suggests that studying telecoupled systems from the perspective of polycentric governance, defined as systems of overlapping jurisdictions with formally independent but interlinked centers of decision-making, could yield valuable insights into how to resolve mismatches in global land and agricultural commodity governance. Beyond examining the effectiveness of single governance institutions in isolation, a more systematic evaluation of the interplay and potential synergies between different governance interventions can advance the understanding of how to design governance solutions that match the scale of the problem at hand.

A social-ecological network approach can be used to study collaborative natural resource governance across jurisdictional boundaries (Janssen et al. 2006, Bodin and Tengö 2012, Barnes et al. 2019). Studies could adopt such an approach to represent telecoupled systems as networks of social actors and ecological resources connected through commodity flows and institutional or social linkages. Although it is difficult to account for different kinds of social actors and the processing of commodities (e.g., from cocoa bean to chocolate bar) with this approach, it can help to capture how material, information, and communication flows connect different ecosystems, actors, and institutions (Janssen et al. 2006, Bodin and Tengö 2012). This approach is particularly suited to the analysis of landscape-scale responses to boundary mismatches because it highlights horizontal institutional interplay, as demonstrated, for example, in research on an agricultural landscape in Madagascar (Bodin and Tengö 2012) and wetlands in Sweden (Bergsten et al. 2014).

Research on telecoupling highlights the need to combine traditional place-based governance approaches with flow-based governance, which "considers a place in light of its relationships with other places, by tracking and managing where key flows start, progress, and end" (Liu et al. 2018:65). Flows are dynamic, and their origin and destination may change over time as a result of, for example, changing infrastructure, market demand, or biophysical conditions (dos Reis et al. 2023). Flow-based governance arrangements such as certification schemes, zero-deforestation commitments, and due diligence laws are designed to govern commodity flows, irrespective of changing trading relationships between supply chain actors. However, flow-based governance may generate new forms of social exclusion, inequality, and ecological simplification in places of production if transnational notions of sustainability do not match with local needs and realities (Newig et al. 2020). This idea highlights that flow-based governance can cover the full spatial scale of telecoupled systems, but their flow specificity comes at the cost of place specificity. Evidence suggests that the effectiveness of flow-based governance benefits from synergistic place-based governance (zu Ermgassen et al. 2022). For example, governments can support the implementation of zero-deforestation commitments by providing additional disincentives for deforestation through, for example, credit restrictions for non-compliant individuals and companies, and through anti-

Fig. 5. Schematic illustration of institutional interactions in a telecoupled system. The circles denote the governance scales of different institutions.



corruption measures that improve the reliability of geospatial forest information on which private governance schemes depend (Garrett et al. 2019). More research is needed to investigate the interplay between institutions that focus on the full spatial extent of the problem and institutions that are adapted to the local context.

CONCLUSION

The governance of telecoupled systems is beset with problems of fit. Because most social and environmental problems in a globalizing world are neither purely local nor global in scale, addressing these problems requires governance responses that transcend political borders to match the spatial scale of the problem while also being sensitive to local context. Here, we applied the established concepts of institutional fit and governance mismatches to complex sustainability issues arising due to telecoupling. We identified two types of mismatches that are pertinent in the governance of telecoupled systems. First, boundary mismatches occur when governance institutions neglect social-ecological problems that transcend established jurisdictional boundaries, either because the institutional design fails to cover the full scale of the problem or because the intervention induces leakages. Second, resolution mismatches arise when governance institutions have a coarser resolution than is suitable to address the social-ecological problem they aim to address. Because of a lack of governance precision, governance instruments are too general to be effectively implemented and enforced. In the context of land and global agricultural commodity governance, approaches such as due diligence laws and policies, landscape and jurisdictional approaches to supply chain governance, and environmental provisions in trade agreements present important steps toward creating institutional fit in the governance of telecoupled systems.

Scaling or rescaling governance to match the scale of telecoupled systems is an inherently political process. The scale at which a given problem is perceived and framed influences the scale at which it is addressed (Newig and Moss 2017). Rescaling governance can entrench, rather than restructure, existing power relations and global inequalities. For instance, companies may stop sourcing from places with weak public governance, where the risk of infringing environmental or human rights is high, and shift to places with stricter governance to meet consumer demands for more transparency and due diligence (Gardner et al. 2019). This effect increases the risk of unintentionally marginalizing small-scale producers in these regions by excluding them from international value chains and the economic benefits of the global economy (Zhunusova et al. 2022). The most vulnerable people and countries may become subject to extraterritorial control and externally imposed notions of sustainability if actors of the Global North seek to govern environmental and social issues beyond their own borders.

We do not claim that rescaling governance institutions to perfectly match telecoupled social-ecological systems will necessarily solve telecoupled sustainability issues, or even that it is attainable in all circumstances. Rather, we acknowledge that the risk of mismatches persists and identifying an “optimal spatial scale” may not be possible. Any attempt to resolve boundary or resolution mismatches comes with the risk of creating new mismatches, and because material flows, immaterial connections, and spillover relations are dynamic (dos Reis et al. 2020), governing telecoupled systems requires recognizing constantly evolving problem structures and continuously evaluating and adapting governance initiatives. However, even if it were possible to create institutional fit, there would be no guarantee of effective governance, due to implementation or enforcement problems. Nonetheless, we see substantial value in distinguishing different types of mismatches in telecoupled settings to be more productive in devising multiple, well-aligned, and adaptive governance arrangements that are better equipped to bring about the required change toward social and environmental sustainability. Looking at land-based commodity flows through the lens of boundary and resolution mismatches helps us to better anticipate potential governance weaknesses arising from a lack of governance precision or extent, and hence, enables better policy debates. Our analysis indicates that complementary interventions at various spatial scales, rather than single interventions, are needed to govern telecoupled systems effectively.

The most pressing and challenging future research question is how to align multiple governance institutions to govern telecoupled systems. Advancing understanding of institutional mismatches in telecoupled systems requires interdisciplinary research, which itself needs to grapple with the challenge of bridging scales embedded in different research approaches, problem definitions, and perspectives (Friis et al. 2023). While we have focused on spatial mismatches in the governance of telecoupled systems, future investigations could analyze the occurrence and implications of temporal mismatches. Telecoupled systems are dynamic, and the spatiotemporal connections between regions and actors can change over time (dos Reis et al. 2020, 2023, Leijten et al. 2022), requiring adaptive governance responses. Additionally, investigating to what extent governance institutions fit with the complete life cycle of products merits further research because the spatial scale of governance expands when the temporal scale of governance is upscaled to the product life cycle. The task, albeit formidable, is to design governance systems in which effective institutional interplay offsets institutional mismatches of single institutions.

[1] Bergsten et al. (2014) note that the two types of mismatches may overlap, for example, when jurisdictional boundaries compel actors to govern ecological processes at too fine a scale.

[2] However, we acknowledge that the different types may overlap or be nested in reality, depending on which governance institution is taken as the analytical vantage point. For example, what appears as a spillover of one governance institution may be an induced leakage of another governance intervention.

[3] For example, the Convention on Biological Diversity, United Nations Convention to Combat Desertification, United Nations Framework Convention on Climate Change, and New York Declaration on Forests are not flow specific.

Author Contributions:

J. C. coordinated the development and conceptualization of the study and wrote the original draft of the manuscript, as well as the revisions. G. S., J. N., P. M., and E. Challies contributed to conceptualizing the study and drafting, revising, and editing, the manuscript; authors' names are listed according to the degree of contribution. S. B., L. B. L., E. Corbara, C. F., A. F. P., P. L., C. P. P., S. Q., N. R., and J. Z. contributed to discussing the concepts at two workshops and revising and editing the manuscript; authors' names are listed alphabetically to indicate equal contributions. All authors approved the final manuscript.

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Data Availability:

Data/code sharing is not applicable to this article because no new data/code were created or analyzed in this study.

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Article III: Why telecoupling research needs to account for environmental justice[2]

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Why telecoupling research needs to account for environmental justice

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Abstract

Engaging with normative questions in land system science is a key challenge. This debate paper highlights the potential of incorporating elements of environmental justice scholarship into the evolving telecoupling framework that focuses on distant interactions in land systems. We first expose the reasons why environmental justice matters in understanding telecoupled systems, and the relevant approaches suited to mainstream environmental justice into telecoupled contexts. We then explore which specific elements of environmental justice need to be incorporated into telecoupling research. We focus on 1) the distribution of social-ecological burdens and benefits across distances, 2) power and justice issues in governing distantly tied systems, and 3) recognition issues in information flows, framings and discourses across distances. We conclude our paper highlighting key mechanisms to address injustices in telecoupled land systems.

Keywords: telecoupling, environmental justice, ecosystem services, power, governance,decolonial thought

Introduction

The expansion of socio-economic globalization has widened the distance between the benefits and costs of land use change. For example, soybean imports from South America have enabled China to avoid domestic agricultural expansion and spare land for afforestation (Torres, Moran, & Silva, 2017). Global soybean demand benefits industrial processing companies, importers and governments of importing and exporting countries (Oviedo, 2015). However, it has led to rapid deforestation in the Argentinian Chaco (Fehlenberg et al., 2017), displacing indigenous peoples and small-scale farmers (Cáceres, 2015; Leguizamón, 2016), and exposing them to flooding and reduced availability of forest products (Camino, Cortez, Altrichter, & Matteucci, 2018).

This example shows how land use change generates social-ecological impacts across distances and scales. The concept of telecoupling helps to explore these effects bylinking globalization with land use change (Eakin et al., 2014; Friis et al., 2016; Lenschow, Newig, & Challies, 2016; Liu et al., 2013). Telecoupled systems are distantly connected social-ecological systems sending and receiving goods and services, energy, matter, information and living species through their enabling agents (Liu et al., 2013). The connected systems (in the example above, deforested lands in Argentina and spared land in China) can also directly or indirectly affect additional "spillover" systems. In our example, these would be the corn and paddy fields that replaced soybean production areasin the Heilongjiang province of China, resulting in nitrogen pollution (Sun et al., 2018).

The novelty and analytical potential of a telecoupling lens is to reveal such distant ties from a social-ecological perspective, while earlier approaches have focused either on ecological or socio-economic aspects (Liu et al., 2013). Nevertheless, telecouplingstudies still need to engage with normative questions in order to deal with the moral consequences of decision-making (Nielsen et al., 2019). This has not happened systematically yet (Corbera, Busck-Lumholt, Mempel, & Rodríguez-Labajos, 2019). We contend that an environmental justice lens can contribute significantly to critically reflect and operationalize the normative dimensions of telecouplings.

In what follows, we first explain why environmental (in)justices are fundamental features of telecoupled systems. We demonstrate why telecoupled systems produce socialand environmental inequalities qualified as unjust, and which approaches of environmental justice are most suited for analysing these situations. Secondly, we explorewhich elements of environmental justice can and should already be incorporated in telecoupling research. We then highlight possible mechanisms towards achieving greaterenvironmental justice in telecoupled systems.

Why telecoupling research needs to account for environmental justice

Because sending and receiving goods through distance implies a redistribution of the environmental costs of their production, environmental inequality is prominent in telecoupled systems. For example, soybeans are consumed in Europe and China while the environmental burdens concentrate at the producing locations in South America.

There is wide empirical evidence that more affluent people and economies can shift the environmental costs of their consumption, such as carbon emissions (Xiong, Millington, & Xu, 2018) or deforestation (Jorgenson, 2006) to distant places. In these places, land use changes due to the production of global commodities have strong negative impacts on socio-economically disadvantaged and disempowered social groups (Borras, Franco, Kay, & Spoor, 2011; Peluso & Lund, 2011). Hornborg (1998) explains the mechanisms that lead to global environmental inequalities through the theory of ecological unequal exchange (EUE). EUE postulates that though raw materials have a greater productive potential and that their extraction hashigh environmental impacts, their monetary value is lower than processed goods (Givens,Huang, & Jorgenson, 2019). In a connected global system where nations have historicallyunequal positions (Wallerstein, 1984), centres of consumption concentrate exchange value while they undermine the productive potential that they absorb through trade fromtheir peripheries. This accumulation of exchange value allows centres to further extract raw materials and cheap labour at their periphery (Martinez-Alier, 2009) and shift environmental burdens and social costs onto those who have less access to consumption of goods and services (Fitzgerald & Auerbach, 2016; Rice, 2007). Though the peripheryoften corresponds to the Global South, unequal exchange and core-periphery dynamics work both within and between nations (Dunaway & Clelland, 2016; W. Zhang et al., 2018).

Why is justice an appealing concept for analysing such unequal social-ecological exchange? Justice is a fundamental evaluative criterion in moral philosophy (Rawls, 1971; Sen, 2009). John Locke (2005 [1690]) showed that justice has an intrinsic value ensuring people the opportunities for a life worth living, as well as an instrumental value (as a ‘social contract’ in Locke’s terms) because justice is considered to be a condition that enables collective action towards goals such as sustainability (Martin, 2013: 99).

Though sustainability and justice are often framed as separate conditions (e.g. Leach et al., 2018), EUE suggests that unsustainable and unjust conditions tend to be causally inter-linked in telecoupled systems. Empirical evidence shows that more unequal societies tend to have more degraded environments, in particular air and water (Cushing, Morello-Frosch, Wander, & Pastor, 2015). Inversely, socially just environmental measures and policies are more likely to be effective (Brondizio & Le Tourneau, 2016; Pascual et al., 2014). Boyce (2018) explains this link through the power-weighted social decision rule: powerful people, companies and nations are less likely to address environmental costs when they can shift them to others who lack sufficient economic and political power to take environmentally relevant decisions.

We postulate that environmental justice provides the most developed framing to understand environmental inequalities and their causes in telecoupled systems. Environmental justice has expanded its initial focus on characterizing environmental burdens among disadvantaged groups (Bullard, 1994) to understand the causes of these inequalities as well as justice claims, discourses and practices in environmental issues (Holifield, Porter, & Walker, 2009). Schlosberg (2007, 2013) has shown that environmental justice issues and claims work along three dimensions: 1) the distribution of environmental burdens and benefits, 2) procedural justice, the fairness and autonomy of environmental decisions-making and 3) recognition justice including issues of rights, power, and respect for cultural differences in knowing and shaping the environment (Martin, 2013).

This framing is particularly relevant for telecoupling research. Distributive environmental justice can help to identify how telecoupling dynamics create winners and losers. Procedural and recognition justice contribute to integrate responsibility and agency perspectives in telecoupling research. Finally, highlighting mechanisms that improve environmental justice in telecoupled systems can enhance the understanding of feedback processes and their transformative potential.

Despite the relevance of environmental justice issues for telecoupling research, few studies have addressed it explicitly. A recent review of 48 telecoupling studies (Corbera et al., 2019) found only three contributions that integrate justice explicitly, and also found that those studies that do integrate justice implicitly generally concentrate on distributive equity aspects. This suggests that studies on environmental justice and telecoupling have remained largely disconnected in the global land systems and sustainability science literatures, with few exceptions (e.g. Boillat et al., 2018; Lundsgaard-Hansen et al., 2018; Oberlack et al., 2018; Schröter et al., 2018; Zimmerer, Lambin, & Vanek, 2018). In the next sections, we discuss each dimension of environmental justice and which related questions and empirical approaches could help enriching the study of telecoupled systems. The table in supplementary material summarizes these questions.

Elements of environmental justice to incorporate into telecoupling research

Distributive justice: benefits and burdens across distances

In telecoupled systems, distributive justice is about the benefits and burdens generated bysocial-ecological flows across distances. This includes “embedded” natural resources andemissions in commodities, such as virtual water (Hoekstra & Mekonnen, 2012), land (Yu,Feng, & Hubacek, 2013; J. Zhang, Zhao, Liu, & Liu, 2016), and greenhouse gases (Xiong et al., 2018). Schröter et al. (2018) conceptualize environmental benefits in telecoupled systems as benefits from interregional flows of ecosystem services, including trade of goods, active and passive biophysical flows and information flows. Pascual et al. (2017) identify negative impacts through ecosystem service burdens that can be distant but alsotemporally delayed and spatially diffuse.

The ecosystem services framing is nevertheless limited by its utilitarian conception of nature and justice that cannot be assumed to be shared among the actors involved (Díaz et al., 2018; Sikor, 2014). The IPBES framework of “nature’s contributions to people” (Díaz et al., 2018) and its adaptation to land systems (Ellis, Pascual, & Mertz, 2019) acknowledges the diversity of valuation languages; it highlightsthe importance of social relations in land systems, the connections between land and multiple dimensions of well-being, and actors’ views about these relations. Accounting for this diversity is particularly relevant in telecoupled systems that span across borders and cultures.

We thus propose to examine the distribution of burdens and benefits in telecoupled systems through a diversity of valuation languages. This requires knowledge co-production methods to assess telecouplings (Zaehringer, Schneider, Heinimann, & Messerli, 2019) and to assess the social impacts of ecosystem change from a multi-dimensional perspective (Daw, Brown, Rosendo, & Pomeroy, 2011; Dawson & Martin, 2015). Such perspective implies to move beyond social outcomes that strictly arise from ecological change (Lele, Springate-Baginski, Lakerveld, Deb, & Dash, 2013) and consider direct social effects of telecouplings, such as changing labour practices in connected systems (Li, 2011), changing terms of trade, entitlements and the control of land and natural resources.

Procedural justice: actors, decision-making spaces, and power

To become operational in terms of justice, burdens and benefits must be linked with actors holding responsibilities and claims. Instead of focusing either on production or consumption-based responsibility, Marques et al. (2012) propose the concept of income-based environmental responsibility (IBER) as an extension of downstream responsibility. IBER considers the suppliers of primary factors of production, including resources, capital and knowledge (e.g. GM seeds developers, financial institutions and large crushing industries in the soybean example) as responsible agents. IBER takes into account whole supply chains and both direct and indirect effects and is in line with the Equator Principles that focus on financial bodies (Marques et al., 2012). This concept or a combination of it with consumption-based responsibility provide a basis to track responsibilities in telecoupled systems.

Procedural justice is about the extent to which legitimate voices and interests of individuals and social groups are represented in decision-making. Inquiring about who is potentially affected by telecoupling processes raises the question of the subjects of justice, namely those considered legitimate holders of claims to social and environmental rights (Sikor, Martin, Fisher, & He, 2014). Rawlsian theory postulates that subjects of justice are the members of a sovereign nation-state. However, this definition falls short in telecoupled systems that typically cross borders (Fraser, 2010a). One should instead referto the all-subjected principle (Fraser, 2010b) which posits that all people that are affectedby governing decisions taken in relation with a telecoupling process or a telecoupled system are subjects of justice.

This leads us to identify decision-making spaces that refer to the set of collectively binding, coordination and steering decisions gathered under the broad concept of governance (Newig, Lenschow, Challies, Cotta, & Schilling-Vacaflor, 2019). From an institutional analysis perspective (Ostrom, 2005), the social spaces in which actors interact and make decisions are called action situations (Ostrom, 2011). In telecoupled systems, local, distant and flow-centered action situations interact in networks and constitute polycentric governance systems (Oberlack et al., 2018). Flow-centered action situations include vertical and horizontal norms, institutions and power relations governing production networks, contract farming, supply chains and the actors who support them (Adams, Gerber, Amacker, & Haller, 2018; Gibbon, Bair, & Ponte, 2008).

We propose that to integrate procedural justice in telecoupling research, one needs to investigate the power balances within and between interacting action situations. Power balance is particularly relevant between responsibilities holders, affected subjects acrossdistant places and accountability bodies which could result from transnational alliances between subjects, advocacy groups and governments (Kumar, 2014). The ability of actorsto bridge physical, social or institutional distances could be used as an indicator of powerin telecoupled systems (Boillat et al., 2018; Eakin, Rueda, & Mahanti, 2017; Kashwan, 2015). As a relational characteristic of actors, this ability is closely linked with recognition justice.

Recognition justice: information flows, framings and discourses

Recognition injustices involve harms linked to discrimination and domination, produced through formal rules (e.g. tenure rules that discriminate against women) as well as informal norms (e.g. prevailing traditional institutions that prevent women controlling land) that disregard some people to make legitimate claims against imposed burdens. Structural inequalities are expressed at multiple scales through institutions, practices, language and symbols, producing problem framings that strongly influence distributive and procedural outcomes (Fraser, 2000; Schlosberg, 2007; Young, 1990).

Global environmental justice literature pays a particular attention to the recognition injustices linked to coloniality (Álvarez & Coolsaet, 2018; Martin et al., 2016; Rodriguez, 2013; Rodríguez & Inturias, 2018). Coloniality postulates that environmental injustices arise because governance spaces are driven by dominant forms of knowledge and values, which in turn shape both problem analysis and solutions in ways that reflect and reproduce colonial power asymmetries and reinforce social distance (De Sousa Santos, 2010). From a telecoupling perspective, these spaces embody and project dominant conceptions of nature in distant places. Though policies often 'recognise' local or indigenous community rights, such safeguards are often undermined by the reproduction of colonial politics of recognition. In mainstream conservation practice, for example, indigenous and local communities must often enter into formal compensation or benefit-sharing schemes, rooted in imposed economistic epistemologies, in order to betaken seriously as conservation agents (Martin et al., 2016).

We thus propose to integrate recognition justice concerns into telecoupling research through an examination of discourses, scale choices, evidence framing, views on nature and views of justice expressed in information flows from a decolonial or more generally critical perspective on dominant values. This focus emphasizes that 'information flows' are rarely if ever innocent of injustice. Information is entangled with issues of 'whose knowledge', 'whose values' and ultimately 'whose justice' is made visible or invisible. Such questions are relevant to everyday practices that are presented as neutral but are in fact deeply political, such as choices over appropriate scales of analysis (Towers, 2000), what subjects of justice are considered (Sikor et al., 2014), what kind of evidence is admissible, and so on. To enhance recognition justice, our analysis of telecoupled systems should therefore employ a 'thickened' sense of information flows that asks whose knowledge, values and interests are considered, and whose are renderedinvisible. This will also require critical reflection on the framing of telecoupling itself. For example, categorizing places as 'sending', 'receiving' or 'spillover' could simplify spatial relations and assume that agency is confined to 'sending' regions (Friis, Nielsen, Otero, Haberl, & Hostert, 2016).

Addressing injustices in telecoupled systems

Telecoupling research can build on insights from environmental justice research on selected, potential mechanisms for transforming environmental justices in telecoupled systems.

First, responses to injustices can be driven by social movements that are increasingly interconnected around common values, concerns and interests (Anguelovski & Martínez Alier, 2014; Temper, Demaria, Scheidel, Del Bene, & Martinez-Alier, 2018).

Through the *boomerang mechanism* (Keck & Sikkink, 1998: 12-13), local activists can purposefully seek transnational allies to draw attention to the existing injustices, mobilize international leverage and eventually reshape power asymmetries (Keck & Sikkink, 1998; Veuthey & Gerber, 2012). These allies can include foreign and international NGOs (Carruthers, 2008; Keck & Sikkink, 1998), financial and trade organizations (Nelson, 2002), courts and tribunals (Spalding, 2017) or company shareholders (McAteer & Pulver, 2009). This mechanism can potentially empower marginalized subjects of justice, defend community rights and resources, reinvigorate local identities and better recognition of local ecological knowledge (Oberlack, Tejada, Messerli, Rist, & Giger, 2016; Villamayor-Tomas & García-López, 2018).

Second, the *catapult mechanism* describes the inverse setting, in which responsesare initiated by transnational actors such as international NGOs who form alliances with local actors. They can harmonize their own agenda with local environmental justice struggles (Temper, 2019) and proactively support the agency of local resource users (Lundsgaard-Hansen et al., 2018). Resistance movements can also scale out their effectsthrough the *minefield mechanism*, through which highly conflictive projects can change the overall perception of similar projects (e.g. in terms of risk and profitability), leading to alterations in investment behaviour, legal action, or regulatory changes (Temper, 2019). For example, wide-spread citizen resistance enhanced the open pit mining ban in Costa Rica in 2010 (Broad & Fischer-Mackey, 2017).

Third, different combinations of public, private and third sector actors collaborate to mitigate environmental justice conflicts through *enhanced transparency* (Anseeuw, Lay, Messerli, Giger, & Taylor, 2013; Gardner et al., 2019). Better public access to information, including environmental data, can constrain elites to extract resource rents and to form patronage networks (Corrigan, 2014; Dillon et al., 2017). Transparency initiatives may provide new means of participation and accountability in land and resource governance (Mejía Acosta, 2013; Vijge, Metcalfe, Wallbott, & Oberlack, 2019).

More mechanisms to transform injustices in telecoupled systems exist, for instance through global institutions or states (Lenschow et al., 2016). The presented mechanisms can interact and involve different configurations of agencies, including those of researchers. Telecoupling research has an inherently transformative power by highlighting processes that link distant responsibilities and claims. Telecoupling researchers should thus engage in research co-design and knowledge co-production processes that require self-reflection on their roles in transforming injustices (Pohl et al., 2010; Temper & Del Bene, 2016).

Conclusion

In this article, we have advocated for the inclusion of a justice perspective in telecoupling research. We have shown how social-ecological flows across distances create winners and losers, how to assess them and under which conditions injustices can be reduced. Because telecouplings are social-ecological interactions, some people in some contexts are likely to bear adverse effects in both social and ecological terms while, in other contexts, telecouplings might not necessarily translate into subjectively felt injustices. In this regard, we would refer to the Rawlsian principle that only processes which do achieve better conditions for the worst off can be labelled as just.

Specifically, we have argued for the incorporation of procedural and recognition perspectives in telecoupling research, which pays increased attention to responsibilities, governance systems, power, discourses and values. Such perspective can contribute to a richer understanding of which mechanisms create and reproduce injustices at different scales for different actors in telecoupled systems and contribute to a more engaged and reflexive role of telecoupling researchers in transforming injustices.

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Governing spillovers of agricultural land use through voluntary sustainability standards: A coverage analysis of sustainability requirements

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ABSTRACT

Voluntary Sustainability Standards (VSS) are prominent governance instruments that define and verify sustainable agricultural land use at farm and supply chain levels. However, agricultural production can prompt spillover dynamics with implications for sustainability that go beyond these scales, e.g., through runoff of chemical inputs or long-distance migrant worker flows. Scientific evidence on the governance of spillovers through VSS is, however, limited. This study investigates the extent to which VSS regulate a set of 21 environmental and socio-economic spillovers of agricultural land use. To this end, we assessed the spillover coverage in 100 sustainability standards. We find that VSS have a clear tendency to cover environmental spillovers more extensively than socio-economic spillovers. Further, we show how spillover coverage differs across varying types of standard-setting organizations and VSS verification mechanisms. Finally, we discuss the role and limitations that VSS can have in addressing the revealed gaps.

1. Introduction

With rising global demand for food, feed, and energy, agricultural land use has become pivotal in causing and addressing many pressing sustainability challenges, such as biodiversity loss, climate change, deforestation, and human rights violations (IPBES, 2019; IPCC, 2020; IRP, 2020). Governments, civil society, and businesses are developing governance interventions to promote sustainable agricultural production and supply chains (Garrett et al., 2021; Lambin et al., 2014). Among these, Voluntary Sustainability Standards (VSS) have become a prominent type of market-based supply chain intervention (ITC, 2021a; Meier et al., 2020). VSS are "voluntary, usually third partyassessed (i.e. certification) norms and standards relating to environmental, social, ethical and food safety issues, adopted by companies to demonstrate the performance of their organizations or products in specific areas" (Lamolle et al., 2019, p. 265). They are developed by different types of standardsetting organizations, including NGOs (e.g., Fairtrade), companies (e.g., ADM Responsible Soybean Standard), governments (e.g., China Green Food), or multi-stakeholder initiatives (e.g., Roundtable for Sustainable Palm Oil). Typically, agricultural VSS grant certifications at the level of production units (plot, farm, or concession) and producer groups, but increasingly also at other supply chain stages.

Syntheses of evidence of on-the-ground impacts of VSS have shown mixed results, revealing different challenges related to the design and implementation of VSS (Blackman and Rivera, 2011; DeFries et al., 2017; Johansson, 2012; Meemken, 2020; Oya et al., 2018; Traldi, 2021). One of the key challenges regarding VSS design is spatial scale mismatches (Tscharntke et al., 2015). These arise when the spatial scale at which VSS seek to foster good practices are incongruent with the scale at which sustainability issues occur (Cumming et al., 2006; Folke et al., 2007; Galaz et al., 2008; Tscharntke et al., 2015). Spillover processes, which are prompted by farm-level practices and have positive or adverse sustainability impacts in near or distant locations, are situated at the core of this VSS challenge (Meyfroidt et al., 2020). A wide range of scientific knowledge demonstrates the relevance of spillovers to sustainability beyond the farm level (Diogo et al., 2022). Cunha et al. (2012), for instance, showed that pesticide spray drift from citrus orchards in Spain can pose significant risks to surrounding aquatic habitats, pollinator populations, and rural communities. Marks and Miller (2022) point to the spread of agriculture-driven air pollution in Thailand, crossing both urban–rural and jurisdictional boundaries. Deininger and Xia (2016) found evidence of positive spillovers from

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large farm establishments in Mozambique on nearby small farms in terms of access to inputs, knowledge, and work opportunities. Being confined to a certain scale of implementation, VSS and other types of supply chain interventions create "islands of good practice" (UNDP, 2019, p. 12), potentially neglecting spillover processes that could support or undermine their sustainability objectives. As a result, the need for governance instruments that are capable of addressing sustainability outcomes beyond farm and supply chain levels has been increasingly recognized (Glasbergen, 2018; Parra-Paitan and Verburg, 2022; Tscharntke et al., 2015).

Despite this importance of spillovers for agricultural sustainability, VSS practice and research has, so far, paid limited explicit attention to spillovers of agricultural land use (Meemken et al., 2021). Related ongoing scientific debates have evolved around indirect effects of VSS adoption (Heilmayr et al., 2020; Heilmayr and Lambin, 2016; Schleifer and Sun, 2020; Smith et al., 2019) and the implementation of VSS in telecoupling contexts, in which land systems are connected across distances (da Silva et al., 2019; Eakin et al., 2017; Garrett and Rueda, 2019). In this emerging field of research, a comprehensive assessment of environmental and socio-economic spillover processes that are triggered by agricultural land use and their regulatory coverage by VSS is currently lacking. There is no evidence of the extent to which existing VSS are already regulating spillovers of agricultural land use and of how this varies across different VSS systems (e.g., private vs public standards). Such knowledge is needed to trigger and inform a critical discussion on the potential role and possibilities of VSS in addressing spillovers, as well as to develop complementary mechanisms to effectively govern them.

This study addresses these gaps by investigating the role of VSS in governing spillovers of agricultural crop production. We ask: 1) To what extent do VSS requirements regulate different types of spillovers? 2) Which VSS characteristics are associated with a higher/lower degree of spillover coverage? We address these questions in four steps. First, we propose a conceptualization of agricultural land-use spillovers tailored to VSS (Section 2). This includes a working definition and its operationalization through a literature review to identify the major types of environmental and socio-economic spillovers. We distinguish 21 spillover processes. Based on these categories, we then conduct a coverage analysis of 100 VSS related to agricultural production, using the Standards Map database of the International Trade Centre (ITC) (Section 3). Accordingly, we assess the extent to which VSS regulate this set of 21 spillover processes, investigate their coverage for environmental and socio-economic spillovers, and explore the linkages between spillover coverage and different VSS characteristics (Section 4). Finally, in Section 5 we deliberate the relevance of addressing spillovers of agricultural land use in research and policymaking, and thereby critically discuss whether VSS can and should address a broad range of spillovers.

2. Conceptualizing spillovers of agricultural land use

Various disciplines have brought forward different concepts that reference spillovers of land use and related cross-scalar processes, as well as their impacts (Lewison et al., 2019; Liu et al., 2018; Meyfroidt et al., 2020; Truelove et al., 2014). In this study, we apply an interdisciplinary land system science perspective to define spillovers of agricultural land use. Recent scientific contributions on telecouplings, i.e. distal connections between socio-ecological systems, have drawn particular attention to the spillover concept (Eakin et al., 2014; Liu et al., 2013, 2018; Meyfroidt et al., 2020). Yet, different conceptions of spillovers exist in land system science. Liu et al. (2018, 2013) defined spillover systems in reference to a telecoupling connection (e.g. trade flows) between a sending and receiving system. They describe them as systems that affect and/or are affected by the respective telecoupling process (e.g., by being an intermediate stopover place in commodity trade flows). Meyfroidt et al. (2020, 2018) focused on land-use spillovers, defining them as processes by which direct interventions or changes in land use in one place have impacts on the use of land in another place. Furthermore, in the context of VSS, the notion of spillovers is sometimes also used to refer to the unintended consequences of the adoption and/or implementation of VSS schemes (Oosterveer et al., 2014; Steering Committee, 2012).

For the present study on VSS, we build upon the definition of Meyfroidt et al. (2020, 2018) and define spillovers of agricultural land use as *socio-economic or environmental processes that are triggered by agricultural land use and affect sustainability in near or distant places outside the farm.* They can be manifestations of socio-ecological flows (e.g., of goods, materials, people, species, capital, information) or actor interactions that interlink the certified farm with nearby and/or distant places (Munroe et al., 2019; Sonderegger et al., 2020). Spillovers can be intended or unintended, and have positive or negative effects on human wellbeing and the environment (Bastos Lima et al., 2019; Meyfroidt et al., 2020). In line with the spillover definition proposed by Meyfroidt et al. (2020, 2018), this definition places emphasis on socio-economic and environmental processes that lead to effects in nearby or distant places (rather than the effects themselves). As shown below, we distinguish 21 such processes. It further focuses on spillovers that occur across geographic rather than temporal scales (for information on temporal spillovers, see e.g. Garrett and Pfaff, 2019; Jacobson, 2014). However, the proposed definition noticeably differs from that of Meyfroidt et al. (2020, 2018) in two main aspects. First, we consider spillovers that have implications for sustainability, rather than for land use only. This more comprehensive approach aligns with the broad scope of VSS and their mission to foster sustainability. Second, we consider only spillovers that are triggered by agricultural land use practices. This includes both land use changes and farming practices, but not governance interventions (e.g., policies or programmes affecting land use). We thus do not focus on leakage processes, a subset of the broader spillover notion which are caused by environmental policy interventions (Bastos Lima et al., 2019). In this sense, we also do not account for spillover processes that are triggered by the adoption of VSS (for example, relating to how VSS adoption affects global and local food security (Oosterveer et al., 2014; Schleifer and Sun, 2020) or deforestation in non-certified properties (Heilmayr and Lambin, 2016)). Instead, we focus on spillover processes that are triggered by on-farm practices and assess those spillovers in terms of the extent to which VSS address them. The farm is thereby considered as the reference system to identify spillovers, as it is also the primary unit of intervention of most VSS.

We use the term "spillover" as an umbrella concept and thereby apply a land system science perspective. In this sense, we adopt a comprehensive approach to define and identify spillovers that considers a wide range of processes potentially affecting the sustainability of agricultural land use beyond the boundaries of a farm. We thereby draw on research that explicitly uses the term "spillovers" or describes related phenomena or processes. This allows for the integration of insights from various scientific disciplines dealing with a range of concepts relating to cross-scalar processes and their impacts, such as: economic externalities (Buchanan and Stubblebine, 1962; TEEB, 2018); pecuniary externalities (Shubik, 1971); spatial externalities (in the sense of Lewis et al., 2008; Parker and Munroe, 2007); agglomeration benefits (Richards, 2018); social interactions, including private life, work, and business relationships (Bernard et al., 2014; Janker et al., 2019); displacement processes (Cernea, 2005; Lewison et al., 2019; Meyfroidt et al., 2013); off-site effects (Van Noordwijk et al., 2004); off-stage ecosystem services burdens (Pascual et al., 2017); interregional ecosystem services flows (Bagstad et al., 2012; Koellner et al., 2018, 2019; Schröter et al., 2018; Serna-Chavez et al., 2014); and cross-boundary subsidies between ecosystems and related edge effects (Cadenasso et al., 2003; Polis et al., 1997). We further draw on literature from the field of telecoupling research, which identifies and discusses distant flows and interactions in relation to agricultural production (see e.g., Eakin et al., 2017, 2009; Friis and Nielsen, 2017; Garrett and Rueda, 2019; Rulli et al., 2019; Zimmerer et al., 2018). Finally, Diogo et al. (2022) point to a number of socio-ecological flows and interactions that are triggered by activities at the farm level and affect sustainability outcomes at multiple geographic scales.

We operationalized the spillover concept by combining a review of literature discussing spillover phenomena in agriculture (in the broader sense as described above) with expert feedback and the coding of VSS requirements. Through an iterative process, we identified a set of major types of spillover processes of agricultural crop production (see Tables 1 and 2 as well as Appendix 1 for more details). We then excluded those spillovers that had insufficient coverage in the database from our analysis (as indicated in Tables 1 and 2 and further detailed in Section 3.4). This set of environmental and socio-economic spillovers is intended to support the process of characterizing a broad range of spillovers of agricultural land use, but it is not exhaustive. Although we chose a comprehensive approach to spillovers, the scope of our study did not cover all potential socio-ecological flows and interactions. For instance, spillovers can also occur along different stages in supply chains, e.g., through commodity or monetary flows or supply chain actor interactions (Barbieri et al., 2021; Malik et al., 2020; Sachs et al., 2019; Xiong et al., 2018). However, we did not consider them in this study as there have already been established efforts to investigate them (see e.g., research on Life Cycle Analysis (Guinée et al., 2011; Hellweg and Canals, 2014) and Material and Energy Flow Accounting (Haberl et al., 2004; Krausmann et al., 2017; Schaffartzik and Kastner, 2019)). Hence, as illustrated in Fig. 1, we focus our analysis on horizontal spillovers that affect sustainability beyond scale at the agricultural production stage of the supply chain, rather than focusing on the vertical spillovers along the supply chain. In addition, we did not consider spillovers relating to norms and values as a separate category (Nash et al., 2017). Any farm-related activities have a normative aspect, and furthermore, all VSS requirements are normative. Hence, the transfer of norms and values is omnipresent in all listed spillovers.

3. Materials and methods

We performed a coverage analysis of VSS requirements to assess the extent to which they cover spillovers of agricultural crop production (see Bissinger et al., 2020; Blankenbach, 2020; Elder et al., 2021; Potts et al., 2014 for similar methodological approaches). Using data from the Standards Map database, we followed a three-step approach: VSS selection; VSS requirements selection and coding; and VSS spillover coverage calculation. We conducted the research in an iterative way, with verification processes built into each of these three steps.

3.1. Data source: the ITC Standards Map

The Standards Map (https://standardsmap.org/) is an interactive web platform providing information about more than 300 VSS in the fields of sustainable trade and production (ITC, 2021b). It is administered by the International Trade Centre (ITC), an agency of the United Nations based in Geneva, Switzerland. It covers a wide range of VSS, such as civil-society-led or industry-led private standards, voluntary public standards, codes of conducts, and international reference documents. The Standards Map is the most comprehensive, standardized dataset on VSS available[1], covering 1650 variables per standard. It contains data on the standards' content (i.e., their sustainability requirements, covering environmental and socio-economic sustainability themes such as soil, energy, waste, human rights, labour practices, and economic viability) and their characteristics (particularly their operating system). The data collection, analysis, and publication processes follow a strict quality assurance protocol that involves independent expert reviews and the respective standard organizations. The database is updated biannually (ITC, 2021c).

For this study, we used the raw data files that feed into the online database. We carefully selected relevant variables, and then cleaned and compiled the data in R. Throughout this process, we were in continuous exchange with the ITC team that manages the database, to ensure adequate use and interpretation of the data. Where data was lacking on VSS characteristics, we completed it with information retrieved from the standards' websites and official documents.

3.2. VSS selection

Using the inclusion and exclusion criteria regarding the VSS scope, use, and implementation shown in Fig. 2, we selected 100 VSS from the Standards Map (see Appendix 2). In this process, we identified VSS that apply to the agricultural sector and the primary production stage (n = 145). We then omitted generic VSS, whose product scope goes well beyond agricultural crops (e.g., also covering products such as diamonds or televisions). Furthermore, we excluded VSS that do not have any conformity assessment system in place (e.g., international guidance documents), to ensure that fulfilment of the standards' requirements is verified. Finally, we excluded those VSS that will expire within 2021 to ensure the actuality of the VSS.

3.3. Selection and coding of VSS requirements

To facilitate the comparison of standards, ITC has developed a set of 659 categories of VSS requirements, against which the contents of individual VSS are mapped. More specifically, the ITC's Standards Map team and the respective standard-setting organization review the standard documents in detail and then allocate individual requirements posed in the standards to a unified set of categories. For each requirement category, an additional set of characteristics (e.g., on degrees of obligation or degrees of criticality) is further noted. Examples for categories of VSS requirements regarding water-related issues are "water extraction/irrigation", "quality of water used in production", and "water dependencies and water scarcity".

We reviewed and coded all 659 VSS requirement categories (hereafter referred to as VSS requirements). Thereby, we selected those relevant to our study (n = 445) and assessed their link with different spillovers (see Fig. 3). Taking a similar approach to Bissinger et al. (2020), we excluded overly broad VSS requirements that could not be assessed in terms of their relevance for our study, as well as those not applicable to the agricultural sector or the primary production stage. We further coded VSS requirements in terms of their correspondence with one or multiple types of spillovers of agricultural crop production (cf. Tables 1 and 2 in Section 2, n = 214). We considered a VSS requirement to correspond with a spillover if they implicitly or explicitly target or affect an immediate trigger of the spillover, the spillover process itself, or a direct impact thereof. For example, for the spillover "water flows", examples of relevant VSS requirements include those relating to soil management measures that affect water infiltration (Smith et al., 2016), water extraction and irrigation (Lankford et al., 2020), water reuse and harvesting (Simons et al., 2015), or assessments of risks and impacts on water levels of water resources used (e.g., groundwater). For the spillover "knowledge dispersion", VSS requirements that fed into our analysis were, for instance, relating to the provision of worker trainings (e.g., fostering knowledge transfers across places as workers may apply the newly learned skills and knowledge in their home (Deininger and Xia, 2016; Zähringer et al., 2018)), or the promotion and use of certain production practices and technologies (e.g., potentially being picked up by other farmers through imitation or knowledge exchange (Albizua et al., 2021; Junquera and Grêt-Regamey, 2019)). VSS requirements targeting indirect triggers or indirect impacts of the spillover processes were not considered for the analysis. Two of the authors of this study

[1] Another topically related database is the Ecolabel Index (http://www.ecolabelindex.com/), which covers a large number of ecolabels (more than 450 as of December 2021), but presents less in-depth information on the content of the standards and is hence less suitable for our analysis.

Table 1
Environmental spillovers of agricultural crop production.

Spillover category	Spillover	Spillover description	Selected references	Analysis
Water spillovers	**Water flows**	On-farm land changes and/or farming practices changing the quantity of surface runoff/excess water or groundwater/aquifer level, affecting nearby/downstream areas (e.g., through limited water availability or floods).	(Bonsch et al., 2015; Bravo de Guenni et al., 2005; Haddeland et al., 2014; Rogger et al., 2017; Stoate et al., 2009)	☑
Pollution spillovers	**Chemical pollutants dispersion**	On-farm land use changes and/or farming practices leading to the emission of chemical pollutants (e.g., chemicals, gases, particulates, or biological molecules) into soil, water, or air, which are then dispersed to nearby or distant areas.	(Felsot et al., 2011; Harrison et al., 2019; Kros et al., 2011; Novotny, 1999; Sagasta et al., 2017)	☑
	Biological pollutants dispersion	On-farm land use changes and/or farming practices leading to biological pollutants (e.g., GMOs, pathogens (viruses, bacteria, parasites) and pests) that are dispersed to nearby or distant areas.	(Bebber et al., 2014; Belcher et al., 2005; Bianchi et al., 2006; Ceddia et al., 2009; Garcia-Yi et al., 2014; Hanson et al., 2004; Woodcock et al., 2016)	☑
Climate spillovers	**Greenhouse gases dispersion**	On-farm land use changes and/or farming practices affecting levels of GHG emissions or sequestration (CO_2, N_2O, CH_4), with respective (avoidance of) climate change impacts elsewhere.	(IPCC, 2020; Pärn et al., 2018; Reay et al., 2012; Schaufler et al., 2010)	☑
	Microclimatic spillovers	On-farm land use changes and/or farming practices affecting the microclimate in the surroundings of the farm (e.g., through changes in air temperature and humidity levels, as well as local wind pattern).	(Laurance and Yensen, 1991; Smith et al., 2013; Stoate et al., 2009)	☑
Soil/earth spillovers	**Soil dispersion**	On-farm land use changes and/or farming practices affecting the risk of water- or wind-borne erosion of organic and in-organic materials (incl. landslides), which are transported to and impact nearby or distant areas.	(Colombo et al., 2005; Quinton et al., 2010; Sagasta et al., 2017; Smith et al., 2016)	☑
	Land subsidence	On-farm land use changes and/or farming practices affecting the sudden or gradual sinking of the ground surface, also outside of the farm area.	(Bagheri-Gavkosh et al., 2021; Galloway et al., 2016; Galloway and Burbey, 2011)	☑
Fire spillovers	**Fire spread**	On-farm land use changes and/or farming practices affecting fire risk, which can spread beyond the farm, with related impacts.	(Barlow et al., 2020; Bravo de Guenni et al., 2005; Cano-Crespo et al., 2015; Leal Filho et al., 2021)	☑
Ecological spillovers	**Species movement**	On-farm land use changes and/or farming practices affecting the ability of organisms (e.g., free roaming predators, pollinators, birds, plant species) to thrive, move and interact across habitats.	(Blitzer et al., 2012; Luskin et al., 2017; Tscharntke et al., 2005; Woodcock et al., 2016)	☑

coded each of the 445 VSS requirements relevant to our study in terms of spillover correspondence and spillover type, resulting in a percentage agreement intercoder reliability of 92.81%. Their coding results were crosschecked, and disagreements were resolved by discussion. In this process, we consulted ITC's detailed guidance information on the VSS requirements and relevant extracts from the VSS documents. In Appendix 3 and 4, the codebook and a summary of the coding outcomes on spillover correspondence are provided.

3.4. *Calculation of VSS spillover coverage*

We conducted two consecutive steps of data aggregation to obtain the extent to which VSS cover different spillovers (see Fig. 4). First, we calculated the standards' coverage of the selected VSS requirements. To this end, we combined data from the Standards Map regarding 1) their degree of obligation (i.e., does the VSS requirement need to be fulfilled immediately?) and 2) their degree of criticality (i.e., how critical is compliance with this VSS requirement?). We assigned scores to different degrees of obligation and criticality, distinguishing between three levels of coverage: mandatory coverage (score = 10), optional coverage (score = 5), and no coverage (score = 0). We then used arithmetic mean to obtain scores for the individual VSS requirements. Secondly, for each spillover type we aggregated the relevant VSS requirements scores to calculate the overall spillover coverage of the standards. We thereby used linear aggregation and equal weighting methods, allowing for compensability between the different scores of VSS requirements. These methods are compatible with each other (OECD and JRC European Commission, 2008) and fit the scale of measurability of our dataset (Ebert and Welsch, 2004; Pollesch and Dale, 2015). As the use of equal weight bears the risk of double counting (OECD and JRC European Commission, 2008; Singh et al., 2012), we tested the VSS requirements allocated to the same spillover types for statistical correlation. We then reviewed pairs of high correlation (>0.8 correlation coefficient) and removed the requirements with the lower score if there was a strong thematic overlap between them.

For the calculation of the individual VSS requirements scores in step 1, we considered three different scoring schemes that account for different degrees of obligation and criticality at varied levels of detail (Fig. 5). We discussed the different scoring options with experts from the ITC Standard Map team to identify potential biases. We adopted scoring scheme A, as it retains important information provided by the database (i.e., whether requirements are mandatory, optional, or not covered), while best accounting for the diversity of VSS and sustainability topics covered in the study. The urgency and criticality of VSS requirements are highly dependent on the type of sustainability issue that they address. While some sustainability challenges call for immediate action and are critical to the standard's mission (e.g., child slavery), others might be more feasibly and purposively addressed through a stepwise implementation of the requirements (e.g., recycling). In addition, different standard systems have different approaches to urgency and criticality (Dietz et al., 2018). For example, besides the more classic pass/fail models, standards systems increasingly incentivize continuous improvement and learning (Rainforest Alliance, 2022; Schmidt et al., 2019). A more detailed score gradient (as in scheme B) would thus bear the risk of introducing a bias in our study, as different degrees of obligation or criticality do not necessarily represent a "better coverage" than another but would otherwise receive higher or lower scores in our analysis. Conversely, a more simplified score gradient such as scheme C would give a similar score to both optional and mandatory requirements, thus fully ignoring different degrees of obligation and criticality. In this sense, selecting scheme A represents a trade-off between making use of the detailed information available in the database and its suitability to our study scope and focus. Nevertheless, we performed a sensitivity analysis to evaluate how the selection of the scoring scheme may influence the results of this study (Section 4.2.3).

The resulting VSS spillover coverage scores (VSCS) indicate the

Table 2
Socio-economic spillovers of agricultural crop production.

Spillover category	Spillover	Spillover description	Selected references	Analysis
People movement spillovers	**People displacement**	Farm-related land tenure changes triggering the displacement/resettlement of people (with certain norms and values, demands for resources, demands for/supply of goods and services), with potential sustainability impacts in the host communities.	(George and Adelaja, 2021; Sridarran et al., 2018; The World Bank, 2014; Verme and Schuettler, 2021)	☑
	Worker migration	On-farm employment practices leading to incoming and potentially returning staff and worker flows (with certain norms and values, demands for resources, demands for/supply of goods and services), with potential sustainability impacts in their place of origin/return.	(King et al., 2021; Levitt, 1998; Rye and Scott, 2018; Seneduangdeth et al., 2018)	☑
Social interaction spillovers	**Knowledge diffusion**	Farm-related activities and interactions leading to a diffusion of knowledge from and to external actors (e.g., through informal knowledge-sharing activities, training for workers or other farmers, imitation), possibly affecting farming practices elsewhere.	(Albizua et al., 2021; Besley and Case, 1993; Junquera and Grêt-Regamey, 2019; Pomp and Burger, 1995)	☑
	Institutional development spillovers	Contributions of farm-based actors to the development and/or shaping of institutions, for instance at community level (e.g., community-based natural resource management), landscape/sectoral level (e.g., cooperatives, labour unions) or at policy levels (e.g., elites' formation, marginalization, political self-organization and representation).	(Candemir et al., 2021; Gruber, 2010; Leach et al., 1999; Oberlack et al., 2016; Ostrom, 2010; Saz-Gil et al., 2021)	☑
	Stakeholder interactions	Engagement of farm-based actors in interactions with communities and other external stakeholders (e.g., worker-community-interactions, or community development and engagement processes which the farm initiates).	(Civera et al., 2019; Janker et al., 2019; McManus et al., 2012; Tunon and Baruah, 2012)	☑
Non-material services spillovers	**Non-material services spillovers**	Farm's (non-)provision of non-material services (e.g., learning and inspiration, physical and psychological experiences, supporting identities), with potential effects beyond the farm level.	(IPBES, 2019; Reid et al., 2005)	☑
Livelihood spillovers	**Resource access spillovers**	Farm-related land tenure changes or activities affecting the access of other people to land, natural and/or cultural resources (through non-market mechanisms), with potential impacts on their livelihoods or wellbeing.	(Cernea, 2005; Dell'Angelo et al., 2017; The World Bank, 2014)	☑
	Services and infrastructure access spillovers	Farm-related land tenure changes or activities affecting the access of other people to basic facilities, services and infrastructure (through non-market mechanisms), with potential impacts on their livelihoods or wellbeing.	(FAO, 2012; Lay et al., 2021; The World Bank, 2014)	☑
Market-mediated spillovers	**Agricultural market spillovers**	Farm-related activities influencing the demand, supply and/or prices for agricultural inputs (e.g., consumable inputs, fixed capital assets, financial capital, labour), outputs and post-harvest services, thus affecting other farmers' access to these markets.	(Ali et al., 2016; Bruntrup et al., 2018; Deininger and Xia, 2016; Heilmayr et al., 2020; Prakash, 2011)	☑
	Non-agricultural market spillovers	Farm-related activities influencing the demand, supply and/or prices for non-agricultural goods (e.g., housing, food) and services, for instance through the presence of migrant workers, thus affecting other people's access to these markets.	(Depetris-Chauvin and Santos, 2018; Doyon, 2009)	☒
	Production displacement	On-farm land use changes and activities triggering a geographic shift in agricultural production through market-mediated mechanisms, with potential sustainability impacts in affected production landscapes.	(Lambin and Meyfroidt, 2011; Meyfroidt et al., 2013; Schoneveld, 2011)	☒
Financial flow spillovers	**Incoming licit financial flows**	Farm-related activities triggering incoming financial flows (e.g., loans, credits, or investments), with implications for the potential private, public, and civic financial sources of the respective flow.	(Lowder et al., 2012; Nolte et al., 2016; Shames et al., 2019)	☒
	Disposable income spillovers	The dispersion and spending of the disposable income of farm-based actors, including remittances, affecting local or distant economies.	(Angelsen et al., 2020; Lambin and Meyfroidt, 2011)	☑
	Farm expenditure spillovers	The farm's non-supply chain-related expenditures affecting local or distant economies (incl. payments of taxes and royalties) with respective impacts on local or distant economies.	(de Janvry and Sadoulet, 2009; Lay et al., 2021; Pangbourne and Roberts, 2015; Roberts et al., 2013)	☒
	Compensation and offsetting spillovers	Farm-related compensation or offsetting payment activities, affecting people and economies in nearby or distant areas.	(German et al., 2013; Lamb et al., 2016; Lay et al., 2021)	☑
	Illicit financial flows	Farm-related activities involving incoming or outgoing illicit financial flows such as bribery payments, e.g., to/from politicians or business partners, or tax evasion.	(Anik et al., 2013; Fink, 2002)	☑

extent to which a certain spillover is covered by a respective VSS. A score of 0 denotes that a VSS does not cover a given spillover at all and 10 denotes full coverage of all VSS requirements relevant to a given spillover. We calculated the scores for spillovers presented in Tables 1 and 2 if they were sufficiently covered in the Standards Map, i.e., we did not consider spillovers that were not covered at all or only covered through a very limited number of VSS requirements (≤5). As a result, we did not consider the following spillovers in the data analysis: spillovers of non-agricultural market mechanisms, production displacement, incoming licit financial flows, and farm expenditure. We presented the methodological approach and results to members of the ITC Standards Map team, discussing their validity and potential interpretations.

In response to research question 2, we linked the VSCS with data on VSS characteristics through means of an exploratory descriptive analysis. We thereby focus on the two characteristics of VSS that are most commonly used to distinguish VSS systems (Fiorini et al., 2019; Lambin and Thorlakson, 2018): 1) the type of standard-setting organization (i.e., company-based, public and other private standards); and 2) the verification mechanism used (i.e., third party and non-third party verification). We used data from the ITC Standards Map regarding the

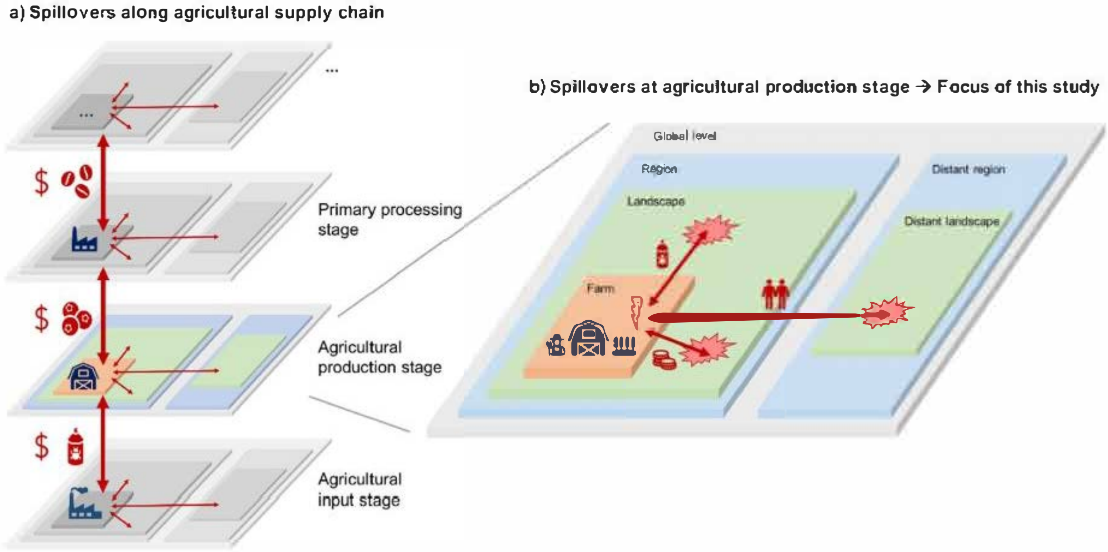


Fig. 1. (a) Spillovers of agricultural production can occur vertically along the supply chain or horizontally across different geographic scales at each stage of a supply chain. (b) This study focuses on horizontal spillovers that triggered at the agricultural production stage and take effect in nearby or distant places through non-supply chain mechanisms (e.g., spillovers relating to pesticide dispersion, worker migration or income spendings). Source: Authors, inspired by Bolwig et al. (2010).

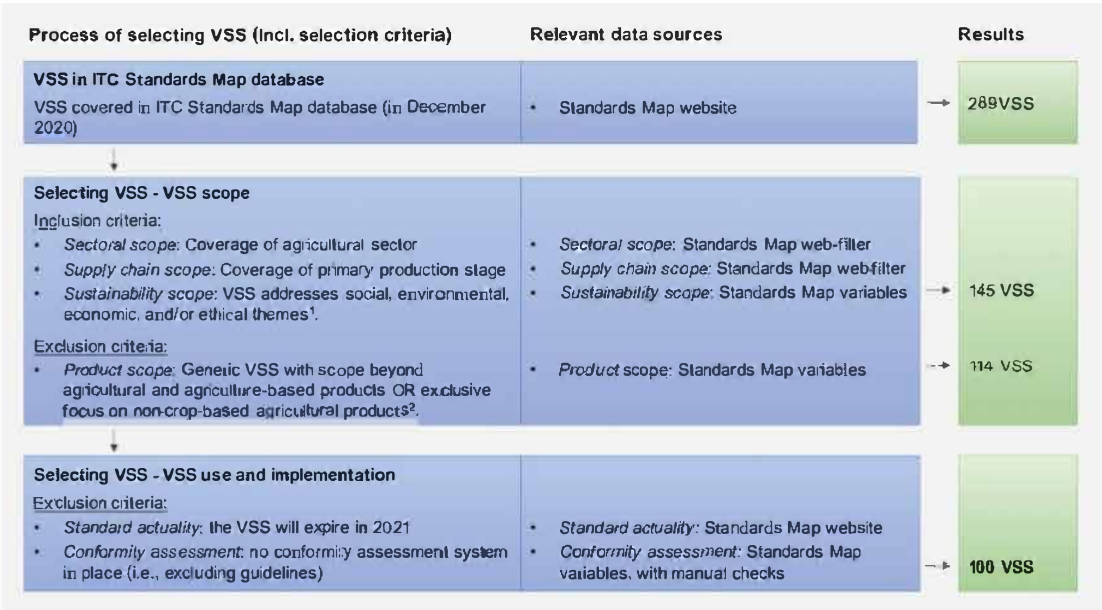


Fig. 2. VSS selection.

[1] We did not include standards that merely focus on product quality, as our research does not focus on spillovers occurring along the agricultural supply chain (see Fig. 1 in Section 2).

[2] This selection was based on the definitions for agricultural crops used for the FAO agricultural census (FAO, 2020).

characteristics of the standards, which we complemented with additional coding based on consultations of VSS documents and the websites of the respective standard-setting organizations.

3.5. Limitations

This study covers VSS that vary largely, for example in terms of the nature and intention of the standard-setting entity or the scope of the products covered (see Section 4.1). The Standards Map database has specifically been designed to compare diverse standards. It thus serves the purpose of this study well, providing a birds-eye view of the subject of spillover coverage in VSS. Nonetheless, the interpretation of our results needs to account for the following limitations in our data source and methodological choices:

First, our sample covers a wide range of VSS that primarily includes private sector initiatives, with less emphasis on public voluntary standards (see Section 4.1). Among the private sector-driven VSS, the Standards Map database has a less extensive coverage of company-based initiatives. In this study, we thus do not aim to cover a representative sample of VSS, but rather to make use of the most comprehensive and

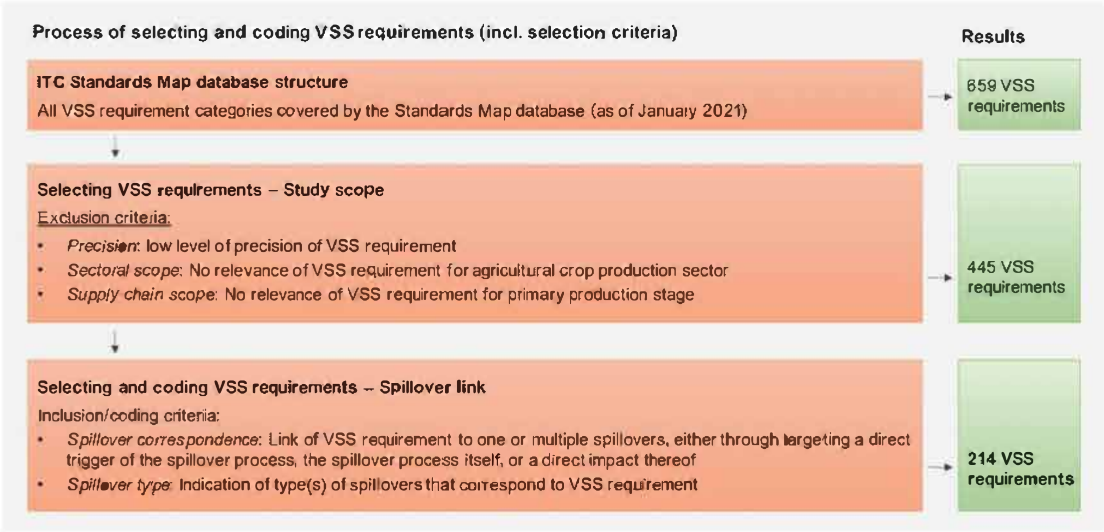


Fig. 3. Selection and coding of VSS requirements.

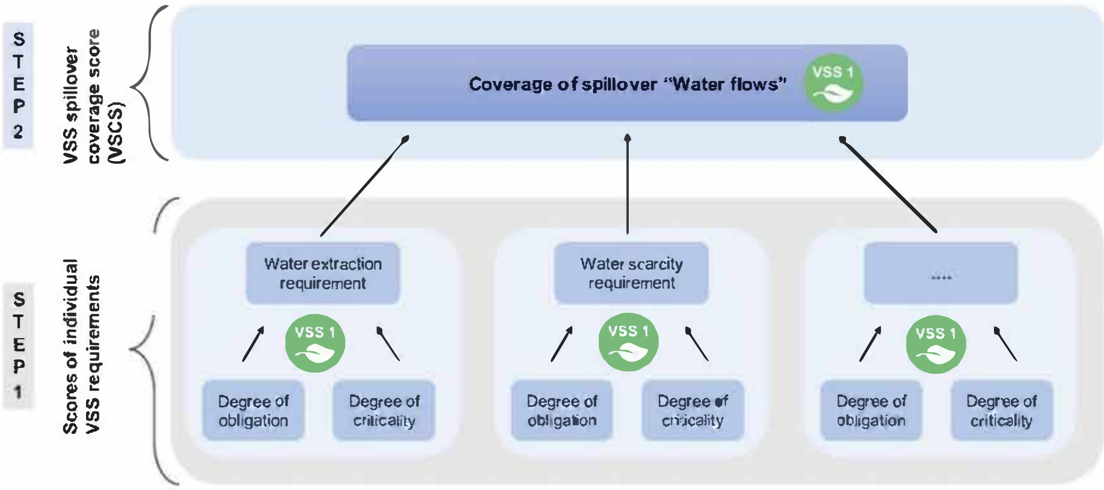
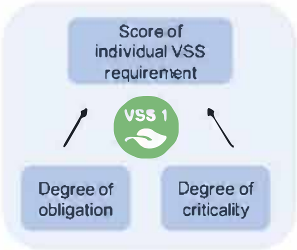


Fig. 4. 2-step approach for calculating VSS spillover coverage, illustrated with the example of the spillover "water flows". Step 1: calculation of the standards' coverage of individual VSS requirements relevant for this spillover, based on their respective degree of obligation and degree of criticality. Step 2: aggregation of the resulting scores of individual VSS requirements to obtain the overall VSS coverage score for the spillover.

extensive global dataset of VSS available to explore the role of VSS in the governance of spillovers.

Second, the ITC database has not been explicitly designed to map VSS content on spillovers, which poses the risk that it may not cover all spillover-relevant contents of the represented standard documents. To assess this issue, we discussed the spillover list with members of the core team of the ITC Standards Map and conjointly deliberated the risk for thematical mismatches with the database. We concluded that this risk is minimal, also based on the wide thematic coverage of the database and regular adjustments of its structure to new standard developments. In addition, during our coding process, we consulted the extracts of standard documents which served as main input to the data presented in the ITC Standards Map, in order to feed our coding decisions with knowledge on the content of the standard documents. Despite these efforts, a certain risk that the database does not fully capture all spillover-related contents of all standards remains. We nonetheless consider the ITC data suitable for this study, particularly given that our study objective is to provide an overview of the spillover coverage of VSS, rather than an assessment of individual standards.

Third, the information that the Standards Map database provides regarding the different types of spillovers varies in both its extent and level of detail. For common regulatory topics (e.g., the use of pesticides in farming practices), information is provided with a greater level of detail. This can result in the presence of multiple variables in the database that address very similar VSS contents. For topics that are less commonly regulated (e.g., incoming financial flows), limited amounts of data points were available. Consequently, the number of VSS requirements used for calculating the spillover coverage of VSS differed considerably across spillovers (as indicated in Fig. 7 in Section 4.2.1). With the applied aggregation method, this can introduce a certain bias in the results. To minimize this risk, we identified the highly correlated variables and removed those with less coverage to prevent double counting. Furthermore, we excluded spillovers with insufficient data availability from our analysis. As a relatively large range of data points for calculating the different spillover types remained, this should be considered when the results are interpreted.



	Scores	Varying degrees of obligation	Varying degrees of criticality	Scores
Scoring scheme A	10	Criteria for immediate action or to be met within 1 year, 3 years, or 5 years	Deal-breaker, major non-compliance, or minor non-compliance	10
	5	Recommendations	Optional compliance	5
	0	Not covered	Not covered	0
Scoring scheme B	10	Criteria for immediate action	Deal-breaker	10
	8	Criteria to be met within 1 year	Major non-compliance	7.33
	6	Criteria to be met within 3 years	Minor non-compliance	4.66
	4	Criteria to be met within 5 years	Optional compliance	2
	2	Recommendations	Not covered	0
	0	Not covered		
Scoring scheme C	10	Criteria for immediate action, to be met within 1 year, 3 years, 5 years, or recommendation	Deal-breaker, major non-compliance, minor non-compliance, or optional compliance	10
	0	Not covered	Not covered	0

Fig. 5. Different scoring schemes for calculating scores of individual VSS requirements, based on different degrees of obligation and criticality. Scoring scheme A was used in the analysis.

4. Results

4.1. *VSS sample description*

The 100 VSS in our sample differ in terms of scope and implementation (Fig. 6). They have primarily been developed by private standard-setters such as non-governmental organizations, industry associations, and multi-stakeholder platforms. Less common are voluntary standards led by private companies (e.g., codes of conduct) or public institutions. Our sample predominantly covers VSS that use independent third-party auditing schemes to assure compliance, but also includes those applying second-party or first-party verification schemes. The majority of included VSS cover multiple agricultural products (e.g., EU organic farming or Rainforest Alliance), whereas others are specialized in certain product groups or sectors (e.g., Florverde, which focuses on the flower sector) or single products (e.g., Buonsucro with sugarcane or 4C with coffee). The large majority of selected VSS are characterized by not-for-profit standard-setters and the use of labels for communication purposes.

4.2 *VSS spillover coverage*

4.2.1. *Degree of coverage for individual spillover types*

VSS regulate different types of spillovers to largely varying extents (Fig. 7). Spillovers of land subsidence have the highest overall degree of coverage (av. VSCS = 4.20) and largest share of VSS with high coverage (28%). VSS mainly regulate this spillover through requirements relating to water extraction and irrigation as well as the conservation of wetlands. The other most frequently covered spillovers are those relating to soil dispersion (av. VSCS = 4.02), water flows (av. VSCS = 3.96), chemical pollution (av. VSCS = 3.79), and biological pollution (av. VSCS = 3.72). Conversely, greenhouse gas dispersion is the environmental spillover type with the lowest average coverage (av. VSCS = 2.68), while fire spread and micro-climatic spillovers present the largest share of VSS with no coverage (22% and 23%, respectively). Pollution related spillovers are covered extensively by the Standards Map; chemical pollution is addressed by 77 VSS requirements, and biological pollution by 50. In contrast, fire spread and microclimatic spillovers are only addressed by 7 and 8 requirements respectively.

Our analysis has revealed that illicit financial flows have the lowest overall coverage in existing agricultural VSS (av. VSCS = 0.70), with 73% of all analysed VSS not covering any of the related VSS requirements (mainly addressing anti-corruption and anti-bribery requirements). Other spillovers with low coverage are those relating to compensation and offsetting payment schemes (av. VSCS = 0.91) or non-material services (av. VSCS = 1.37). Of the socio-economic spillovers, disposable income spillovers have greater coverage by VSS (av. VSCS = 2.99, with 8% of the analysed VSS having a high coverage).

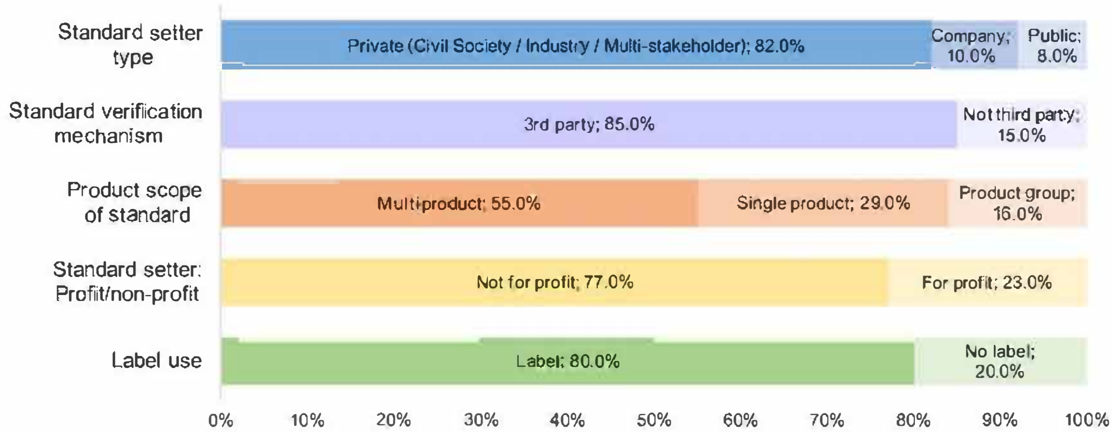


Fig. 6. Relative frequency of VSS characteristics in our sample. (Source: ITC (2021b), completed with information from the standards' websites and official documents and based on calculations by authors).

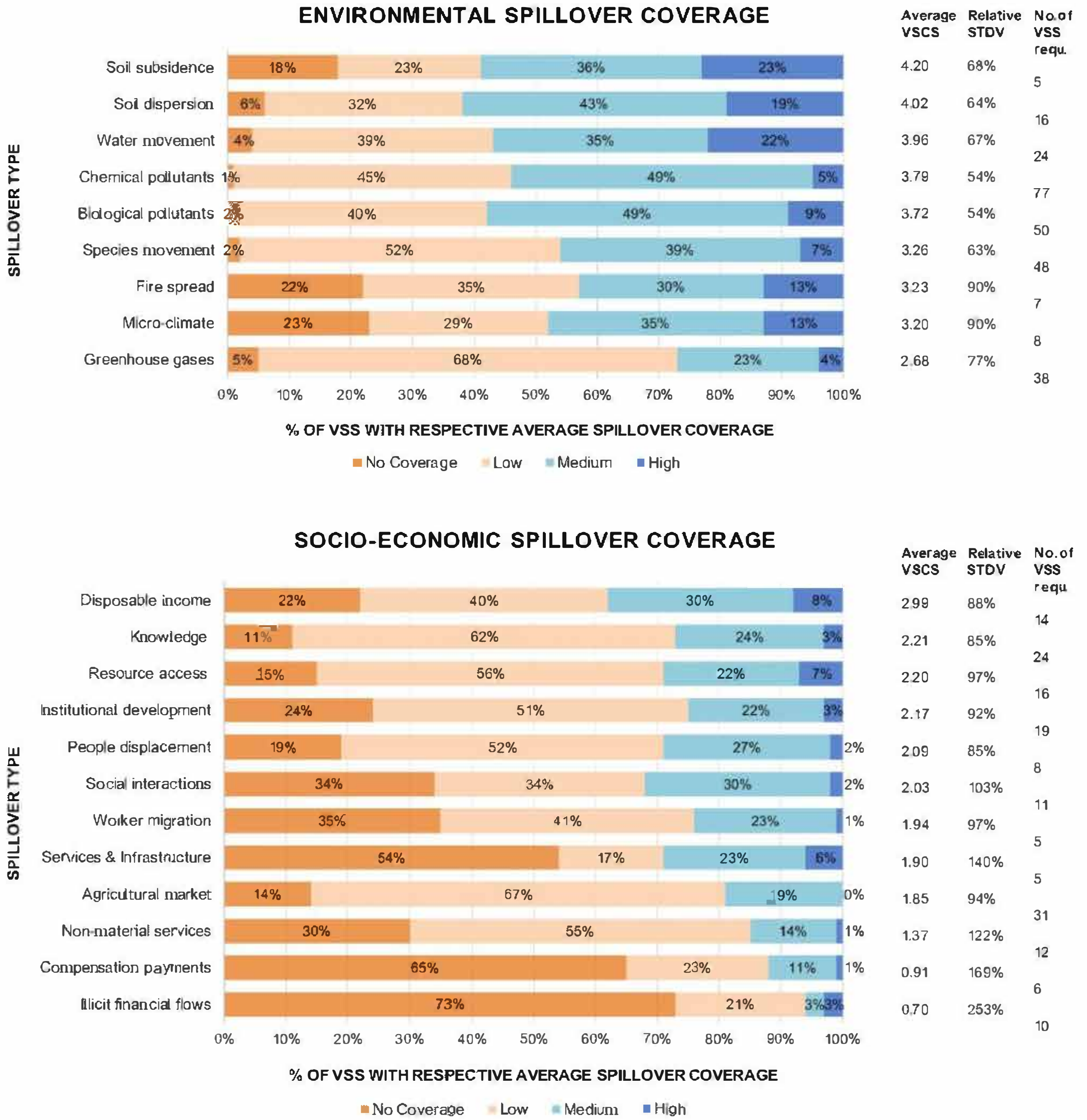


Fig. 7. Relative share of VSS with different levels of spillover coverage, by spillover type and ordered by average VSS Spillover Coverage Scores (VSCS). VCSC scores are grouped into different ranges of coverage: "No coverage": VCSC = 0; "Low": VCSC = 0-3.33; "Medium": VCSC = 3.34–6.66; and "High": VCSC = 6.67–10 (left). The absolute average VSCS, ranging from 0 to 10, as well as the relative standard deviation and the number of VSS requirements available in the Standards Map database, are also displayed (right). (Source: ITC (2021b), based on calculations by authors).

Socio-economic spillovers are in general covered less extensively by the Standards Map database. The numbers of VSS requirements relevant to these spillovers range from 5, for regulating worker migration flows or access to services and infrastructure, to 31, for agricultural market spillovers.

Socio-economic spillovers, in general, have much lower coverage than environmental spillovers in terms of both average coverage score and high coverage shares. VSS tend to score more highly for environmental spillovers (13.3% on average) than for socio-economic ones (3.08% on average). The average share of VSS not covering any of the criteria allocated to socio-economic spillovers is 33.0%, while for environmental spillovers it is only 8.3%. In addition, socio-economic spillovers generally have a larger relative standard deviation of VSS coverage scores than environmental spillovers (relative $STDV_{soc\text{-}eco}$ = 119%; relative $STDV_{env}$ = 70%). This indicates that the heterogeneity among individual VSS in term of spillover coverage is much larger for socio-economic spillovers than for environmental spillovers. One could argue that the lower overall score and high heterogeneity is due to the lower number of requirements allocated to socio-economic spillovers. However, that is not necessarily the case, as there are also environmental spillovers with comparably low numbers of requirements and yet higher overall VSCS scores and low heterogeneity (e.g., soil subsidence).

4.2.2. *Socioeconomic and environmental spillover coverage*

Our analysis reveals a positive association between the average coverage scores of socio-economic and environmental spillovers by individual VSS (Fig. 8). This result implies that most VSS have a similar degree of (implicit) ambition to cover environmental and socio-economic spillovers. Examples of standards that deviate from this trend are the standards of the Wine and Agricultural Ethical Trading Association (WIETA), which predominantly covers socio-economic spillovers, or the RedCert EU standards, which have an increased focus on environmental spillovers.

Fig. 9 indicates the environmental spillover coverage scores for each VSS, in relation to their respective overall coverage score for requirements relating to environmental sustainability (i.e., including both spillover-related and non-spillover-related VSS requirements). We can see that the majority of VSS (80%) have a higher score for environmental spillover coverage than for overall environmental requirement coverage (i.e., they are located above the red-shaded area in the graph), with an average relative difference of 1.07. VSS requirements for environmental sustainability thus show a tendency to regulate management practices that potentially (also) have impacts outside the farm (e.g., water management practices affecting downstream water bodies).

Fig. 10 shows the socio-economic spillover coverage scores for each VSS, in relation to their respective overall coverage score for requirements relating to socio-economic sustainability. In contrast to Fig. 9, most VSS (81%) have a higher score for overall socio-economic requirement coverage than for socioeconomic spillover coverage (i.e., they are located below the red-shaded area in the graph), with an average relative difference of 0.73. This might indicate that, in general, socio-economic requirements in VSS preferentially tend to target socio-economic outcomes affecting actors within the farm (e.g., labour rights), rather than socio-economic spillovers.

4.2.3. *Sensitivity analysis*

The sensitivity analysis (Table 3) reveals that the overall spillover coverage scores are affected by the adopted scoring scheme. In particular, when comparing scoring schemes A and B, we observe that average VSCS are systematically lower for all spillover types in scheme B. This is due to the combined effect of distinguishing gradients scores for varying degrees of obligation and criticality, and particularly, assigning a lower score to recommendations and optional compliance requirements. In contrast, when comparing schemes A and C, we observe that average VSCS are systematically higher in scheme C for virtually all spillover types (except for illicit flows and people displacement spillovers). The

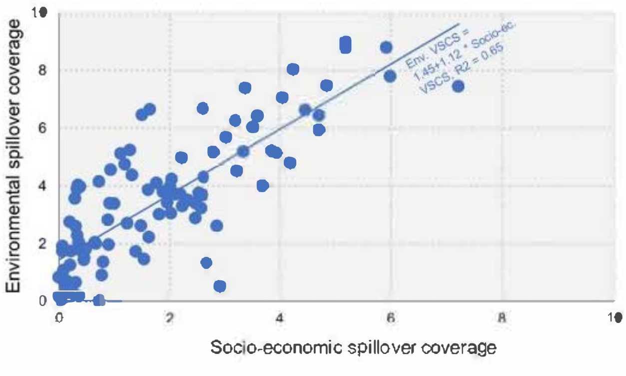


Fig. 8. Average environmental and socioeconomic spillover coverage scores for each VSS. (Source: ITC (2021b), based on calculations by authors).

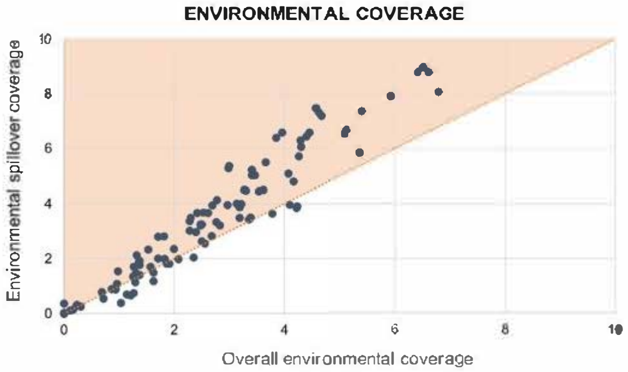


Fig. 9. Environmental spillover coverage score in relation to overall coverage score of environmental sustainability requirements, per VSS. (Source: ITC (2021b), based on calculations by authors).

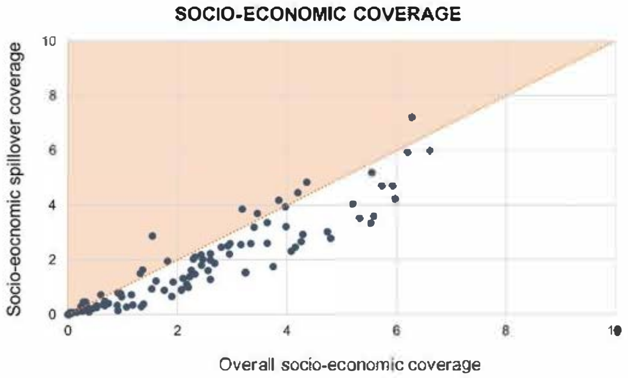


Fig. 10. Socioeconomic spillover coverage score in relation to overall coverage score for socio-economic sustainability requirements for each VSS. (Source: ITC (2021b), based on calculations by authors).

absolute magnitude of the relative deviation is, however, much smaller for scheme C (ranging from −3% to 5%) than for scheme B (ranging from −13% to −25%). We can thus conclude that distinguishing varying degrees of obligation and criticality has a larger effect on the overall spillover score than only distinguishing between coverage/no coverage. Despite these results, we also observe that the effect of each scoring scheme on the final scores appears to systematically have roughly the same magnitude and direction across all spillover types. Hence, we conclude that the selection of scoring scheme does not affect our study results in terms of comparing the relative coverage of different types of spillovers among a selection of VSS.

4.3. *Linking VSS spillover coverage and VSS characteristics*

An explorative comparison of VSCS across different VSS characteristics shows different patterns of VSS spillover coverage (Fig. 11). Different types of standard-setting organizations seem to prioritize certain socio-economic spillovers. Company-based standards (e.g., codes of conduct, n = 10) cover spillovers relating to stakeholder interactions (av. VSCS = 3.27) and institutional development (av. VSCS = 3.18) most extensively. Other private standards (e.g., promoted by multi-stakeholder platforms, industry platforms or NGOs, n = 82)) have a relatively higher coverage of spillovers such as knowledge diffusion (av. VSCS = 2.40) or nonmaterial services (av. VSCS = 1.51). Public standards (n = 8) appear to have a particularly low coverage of socio economic standards (av. $VSCS_{soc-eco}$ = 0.26) and they also cover environmental spillovers less extensively than company-based and other

Table 3
Sensitivity analysis results.

Spillover	Scheme A	Scheme B		Scheme C	
	Average VSCS	Average VSCS	Deviation to A (in %)	Average VSCS	Deviation to A (in %)
Water flows	3.96	3.21	−19%	4.06	3%
Chemical pollutants	3.79	3.11	−18%	3.84	1%
Biological pollutants	3.72	3.11	−16%	3.76	1%
Greenhouse gases	2.68	2.17	−19%	2.74	3%
Micro-climate	3.20	2.69	−16%	3.28	2%
Soil dispersion	4.02	3.28	−19%	4.12	2%
Soil subsidence	4.15	3.30	−20%	4.22	2%
Fire spread	3.23	2.59	−20%	3.29	2%
Species movement	3.26	2.71	−17%	3.30	1%
People displacement	2.09	1.81	−13%	2.06	−1%
Worker migration	1.94	1.64	−16%	1.96	1%
Knowledge diffusion	2.21	1.73	−22%	2.24	1%
Resources access	2.20	1.86	−15%	2.20	0%
Services & Infrastructure	1.90	1.43	−25%	1.98	4%
Institutional Development	2.17	1.84	−15%	2.19	1%
Stakeholder interactions	2.03	1.68	−17%	2.05	1%
Non-material services	1.37	1.17	−14%	1.38	1%
Agricultural market	1.85	1.51	−18%	1.87	2%
Disposable income	2.99	2.47	−18%	3.04	1%
Compensation & offsets	0.91	0.68	−25%	0.95	5%
Illicit financial flows	0.70	0.59	−15%	0.68	−3%

private standards. The latter two types of standard setters show similar patterns of environmental spillover coverage, with the exception of spillovers relating to the spread of fire and soil subsidence.

Relating the VSCS to the prevailing VSS verification mechanisms, our study reveals that standards with third-party auditing schemes (n = 85) generally have a higher coverage of spillovers. This pattern is particularly pronounced for environmental spillovers, but also occurs frequently for socio-economic spillovers. Conversely, for illicit financial flows, considerably higher coverage is achieved by VSS with no third-party verification (av. VSCS = 1.53, n = 15) than by those that use independent third-party auditing schemes (av. VSCS = 0.55).

5. Discussion

5.1. Spillovers, sustainable agricultural land use, and spatial scale mismatches in VSS

Growing awareness of interconnectivity between nearby and distant land systems shapes our understandings of current sustainability challenges, as well as attempts to govern them (Challies et al., 2014; Eakin et al., 2017; Munroe et al., 2019; Newig et al., 2020). Therefore, a comprehensive and integrative notion of sustainable agricultural land use requires explicit consideration of the processes that link agricultural practices with impacts beyond the farm in near and distant places, i.e., spillovers of agricultural land use. This study has identified 21 environmental or socio-economic spillovers of agricultural crop production. It builds on and extends previous research on spillovers with specific thematic foci (e.g. land-use spillovers (Meyfroidt et al., 2020, 2018) and deforestation spillovers (Fuller et al., 2019; Heilmayr et al., 2020)) or related concepts (e.g. off-site impacts or externalities (Buchanan and Stubblebine, 1962; Lewis et al., 2008; Van Noordwijk et al., 2004)). It draws on telecoupling research define and conceptualize sustainable agriculture. We hope to contribute to this field by presenting an elaborate, although non-exhaustive, overview of the processes that couple a farm system with other socio-ecological systems, with an explicit focus those that are triggered by agricultural production. This study further also complements recent scientific contributions investigating the presence and distribution of impacts of agricultural production along the supply chain, for example regarding local impacts embedded in international trade flows (e.g., Chaudhary and Kastner, 2016; Dalin et al., 2017; Oita et al., 2016; Qiang et al., 2020; Roux et al., 2021).

The scales of spillovers of agricultural land use can range from neighbourhood to landscape to transcontinental flows and interactions. They can have significant positive and negative impacts on the environment or human wellbeing, even in places far from the site of agricultural production. In the presence of spillovers, the notion of sustainable agricultural land use can thus no longer be confined to the scales of individual production units; it needs to account systematically for spillovers. Spatial scale mismatches arise if the scales of governance arrangements do not fit the scale of the spillover problem (Cumming et al., 2006; Folke et al., 2007; Galaz et al., 2008). This constitutes a key design challenge for VSS that are intended to foster sustainable agriculture and yet are predominantly implemented at the production unit level (Tscharntke et al., 2015). Here, we highlight two main points of reflection regarding this issue:

First, our study shows that VSS can strive to make important contributions to sustainability beyond the farm level, even if they are implemented at the production unit level. For instance, by regulating the use and application of pesticides, the dispersion of chemical pollutants to nearby areas or within the wider landscape (e.g. through pesticide drift or leaching processes) can be addressed (Sagasta et al., 2017), contributing to biodiversity-related and health-related sustainability within the larger region. The explicit consideration of spillover processes in VSS can thus help to reduce challenges related to spatial scale mismatches in VSS design. Our results have shown that the extent to which VSS regulate spillovers, however, varies largely among different types of spillovers. VSS commonly address spillovers relating to environmental flows, but they often have considerable regulatory gaps with regards to socio-economic spillovers. These results are in line with previous arguments suggesting that VSS may not sufficiently account for spillovers (Heilmayr et al., 2020; Meemken et al., 2021; Smith et al., 2019). However, in view of discussing the potential of VSS making sustainability contributions beyond the farm level, it is important to highlight that our analysis of VSS requirements only provides indications of the aspired change by VSS, rather than the actual impact of VSS on the ground. Hence, even if spatial scale mismatches are (partially) addressed through the more systematic integration of VSS perspectives in VSS design, this does not preclude potential challenges relating to the implementation of the respective standards.

Second, even though VSS implemented at the farm level can *contribute* to sustainability beyond the farm, they may not be able to *ensure* sustainability at larger scales (Schneider et al., 2014). VSS can play an important role in regulating spillovers arising from practices at certified farms, but they cannot regulate spillovers that arise from other,

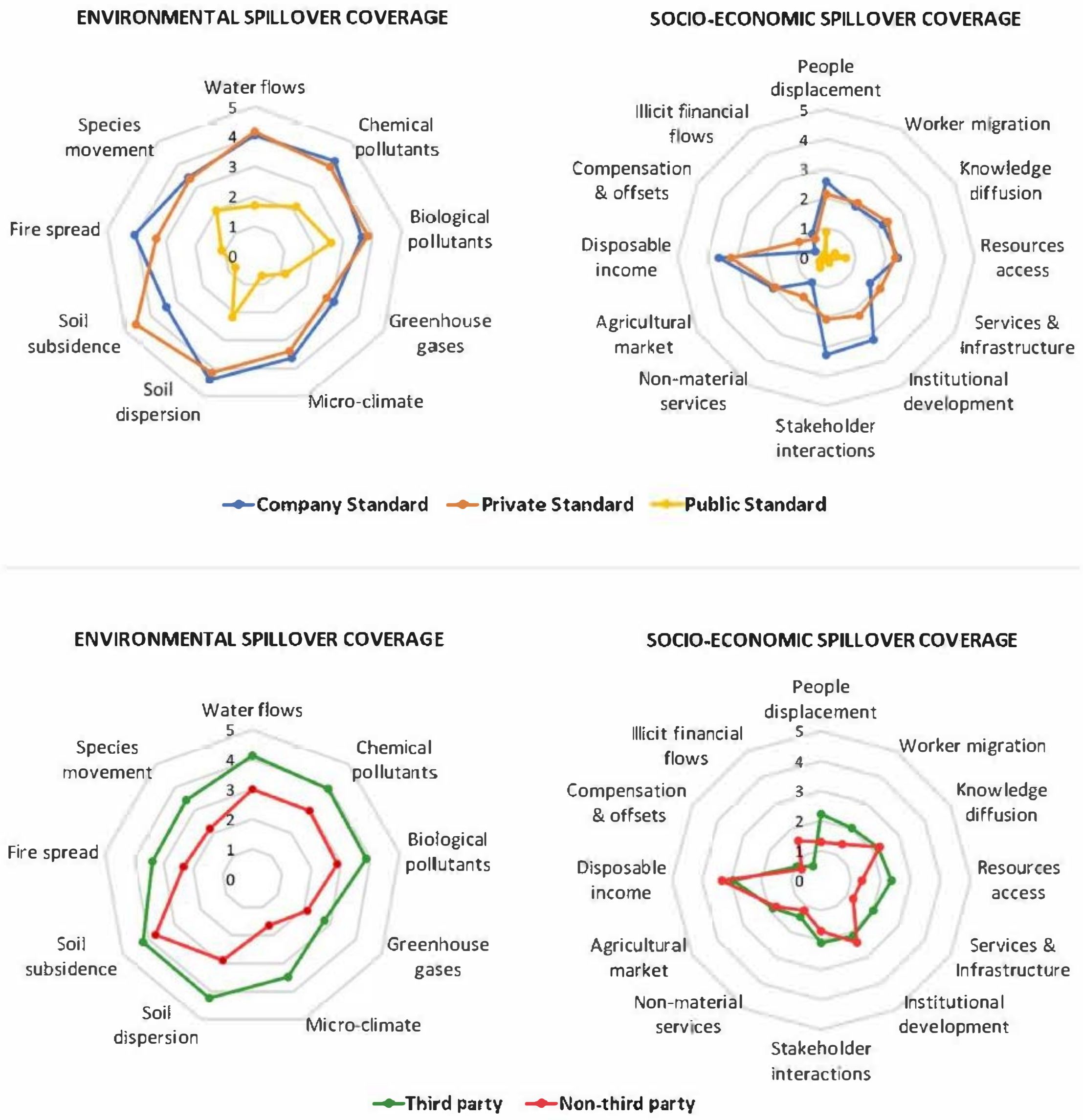


Fig. 11. VSS spillover coverage scores by type of standard-setter (upper panel), VSS verification mechanism (lower panel). (Source: ITC (2021b), based on calculations by authors).

non-certified farms. For instance, VSS aspiring to combat deforestation may be able to prevent farmers from cutting down trees within their certified production unit, but not in surrounding farms (Molenaar, 2021). Aggregated changes in a landscape structure resulting from individual farm-level decisions on the conversion of (semi-) natural habitats can, however, have important effects on biodiversity and provision of ecosystem services within the wider landscape (IPBES, 2019). In this sense, spatial scale mismatches remain an inherent challenge for VSS, as they cannot be fully resolved through farm-level standards. In recent years, the VSS community has increasingly tended to this issue, emphasizing the need to support sustainability at broader scales. Standard-setting organizations have thereby shown a growing interest in linking their activities with multi-stakeholder initiatives at the landscape or jurisdictional levels, moving towards the integration of landscape approaches into their standard systems (ISEAL Alliance, 2017; Mallet et al., 2016). These recent developments could offer promising opportunities for addressing many of the challenges around spatial scale mismatches in VSS and may benefit from the knowledge on spillover processes presented in this study.

5.2. Should VSS cover a broad range of spillovers?

The spillover coverage gaps revealed in this study suggest that VSS standard-setting procedures could lack systematic identification, assessment, and consideration for spillover processes. Should standard-setting organizations therefore work towards filling these gaps, aspiring to address a broad range of spillovers of agricultural land use?

A broad thematic coverage of sustainability standards is often assumed to lead to better VSS performance (Potts et al., 2014). Contrary to this intuitive belief, broad VSS coverage does not necessarily imply good performance, as other factors such as institutional design, market coverage, and implementation and enforcement mechanisms also often play an important role therein (Bissinger et al., 2020; Potts et al., 2014, 2017; Smith et al., 2019). Broader VSS coverage may indeed involve greater risks in designing and implementing VSS. First, more rigorous and extensive standards are likely to lead to higher production costs

(Tscharntke et al., 2015). It is the inherent nature of spillovers that the producers themselves are less likely to benefit directly from the additional efforts needed to mitigate negative or foster positive spillovers. If not compensated sufficiently, the resulting opportunity costs could thus further increase the risk of smallholder exclusion from participation in certification schemes (Fiorini et al., 2019; Grabs, 2020; Starobin, 2020; UNCTAD, 2021). Second, expanding the coverage of standards could further enhance the already frequently high costs for auditing and monitoring, potentially placing additional financial burdens on farmers and nurturing incentives to cheat (Meemken et al., 2021; Schilling-Vacaflor et al., 2020). In addition, the consideration of socio-economic spillovers in particular may require auditors to deal with sensitive and less tangible issues (e.g. land rights or discrimination), which are particularly difficult to monitor and measure (Meemken et al., 2021; Molenaar, 2021). Third, expanding the scope and rigour of sustainability standards could directly contrast efforts to scale up VSS certification. There is a risk that supply chain actors will replace more ambitious VSS with weaker ones or adopt less ambitious standards (Tscharntke et al., 2015). Becoming more ambitious in terms of covering spillovers more comprehensively in VSS might thus contribute to a "race to the bottom" and thereby even negatively affect the overall impacts of VSS (Dietz et al., 2018).

An extensive coverage of spillovers may also lie beyond the scope or possibilities of individual standards. VSS differ in terms of the scope of their objectives as well as their foci on commodities, sectors, and sustainability issues (McDermott, 2013; Tröster and Hiete, 2018). Hence, certain topic areas and their related spillovers may not be of equal relevance. In addition, while this study has focused on the requirements postulated in the standard documents, standard-setting organizations might also employ other tools to address spillovers (e.g., complaint mechanisms). Our study thus does not point to the performance of individual standards, but rather presents a sector-wide overview of priorities and potential gaps in the coverage of spillovers in VSS. However, our results regarding the linkages between VSS spillover coverage and VSS characteristics (Section 4.3) suggest that differences exist among different types of VSS systems and their coverage of individual spillovers. Exploring the reasons and dynamics behind these results offer interesting avenues for further research. To understand better the limitations and opportunities for governing spillovers through VSS, the following questions could be explored further: What are the successful strategies through which VSS currently govern spillovers? Which types of spillovers are best suited to be regulated by (which types of) VSS? What are limitations of VSS to address sustainability beyond farm level?

Furthermore, standard systems do not operate in isolation and interact with other governance instruments (e.g. public policies or international trade regulations) that might be better equipped to address (certain) spillovers (Lambin and Thorlakson, 2018). Literature on VSS effectiveness points to a number of challenges related to the design and implementation of sustainability standards. For instance, VSS have been criticized for ineffective monitoring and enforcement procedures (Schilling-Vacaflor et al., 2020), a selection bias in the uptake of VSS (Lambin et al., 2018; Meemken et al., 2021) or lacking inclusion of smallholders in the governance of VSS (Bennett, 2017; Renckens and Auld, 2019; Schleifer et al., 2019). As indicated in the previous section, some implementation challenges could even further exacerbate through an extensive spillover coverage in VSS. However, as new governance mechanisms are emerging to address sustainability challenges in global supply chains (e.g., due diligence laws (Schilling-Vacaflor and Lenschow, 2021)), this calls for more research about the complementary roles that different governance mechanisms (can) play in regulating spillovers of agricultural production.

In sum, spillovers can be highly important in terms of achieving sustainable agricultural land use. However, as we have shown in this section, simply broadening the coverage of standards to address a multitude of spillovers can exacerbate existing challenges of VSS and may fall beyond the scope of the objectives of certain VSS. In today's interconnected world, positive and negative spillovers will always exist. Efforts should thus be placed not only on identifying potential spillover processes *per se*, but more importantly, on identifying the most relevant processes in terms of their sustainability impacts and existing possibilities for regulating them (TEEB, 2018). In order to foster sustainability beyond scale, standardsetting organizations should thus identify and select carefully those spillover processes with strong potential for supporting or undermining their sustainability targets, and then consolidate efforts towards fostering practicable solutions for governing them effectively, within and beyond the immediate realm of the standard.

5.3. Moving forward: the role of scientific knowledge

Good practice guidelines on standard-setting postulate that VSS should "reflect best scientific understanding" (ISEAL Alliance, 2014, p. 8). There are, however, a number of critical challenges for the uptake of scientific knowledge on spillovers in the operationalization of VSS. Spillover processes and the causal mechanisms leading to sustainability impacts are conceptually complex and difficult to assess, as they evolve dynamically and potentially across scales and large distances. This is to some extent reflected in the current lack of agreedupon definitions and guidelines for defining spillover processes. Research on spillovers is largely scattered across different scientific disciplines, each of them using specialized concepts, methods, and jargon. The absence of a harmonized understanding of spillovers in the scientific domain constitutes on itself a major barrier for developing standardized sets of rules through which spillovers could be taken up in existing VSS.

With regards to individual types of spillovers, our study suggests that spillovers that are less studied and/or more difficult to measure may be particularly challenging to be regulated through standards. In general, we found that environmental spillovers tend to be covered more extensively than socio-economic ones. Many of the environmental spillovers commonly addressed by VSS, such as those relating to dispersion of soil or chemical pollutants, have been subject to scientific research for a long time (Kristiansson et al., 2021). Consequently, more well-defined approaches to observe, quantify and mitigate them exist. Social sustainability in agriculture, contrarily, has received relatively little scholarly attention (Janker and Mann, 2020). As also indicated by Alexander et al. (2020), it is particularly difficult to be operationalized and has received less attention in many VSS.

This study presents a first attempt to contribute to a more comprehensive understanding of spillovers of agricultural production. Yet, in order to facilitate the integration of spillovers into VSS, more efforts are needed to foster transformative sustainability research about a broad range of spillovers (Liu et al., 2018) and to develop approaches for communicating the resulting knowledge in an accessible way to different types of stakeholders (e.g., through visuals, see Sonderegger et al., 2020). Inter- and transdisciplinary cocreation of knowledge and knowledge platforms navigating the related science-policy-society interface (e.g. the Evidensia platform (https://www.evidensia.eco/)) may thereby offer valuable opportunities to foster dialogues about sustainable agriculture in an interconnected world (Burch et al., 2019; Jacobi et al., 2022; Wibeck et al., 2022).

6. Conclusions

VSS are widely used tools for promoting and fostering sustainable agricultural production at farm or supply chain level, with a tendency to grow further in relation to public and private actors. In recent times, standardsetting organizations have increasingly striven to achieve impact beyond the scale of farms or other production units, aiming to address potential scale mismatches in their VSS design. These developments call for a better understanding of spillovers of agricultural production. A spillover lens can help to identify and reflect on the standards' current and potential contributions to sustainable agriculture beyond scale. In this study, we have identified 21 socio-economic and environmental spillovers of agricultural production and analysed their coverage in 100 agricultural standards. We found that many spillover processes are – at least implicitly – already present in the standards' requirements. However, our study has also revealed considerable gaps of spillover coverage in the VSS landscape. In particular, socio-economic spillovers are often not regulated through existing VSS, or only to a limited extent. To explore our full potential for achieving sustainable agriculture beyond the farm level, it is thus important to integrate spillover perspectives into standard-setting procedures.

Spillovers are omnipresent in our interconnected world. Hence, effective spillover governance requires a systematic identification of a range of spillovers and a thorough assessment of the feasibility and purposefulness of governing them, followed by a careful selection of the most relevant ones. This study may serve as a starting point for identifying potentially relevant spillovers. However, a more detailed suite of tools to support and guide the VSS community throughout the overall process of integrating spillovers into VSS governance, and potentially also other governance instruments, is currently lacking. To achieve effective development of the tools needed to support decision-makers, an engaged science-policy-society dialogue is essential. Fruitful dialogues between researchers, standard-setting organizations, and other key players (e.g., policymakers and civil society organizations) about the possibilities, needs, and responsibilities relating to the governance of spillovers is needed to move conjointly towards sustainable agriculture beyond scale.

CRediT authorship contribution statement

Gabi Sonderegger: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Andreas Heinimann:** Writing – review & editing, Supervision. **Vasco Diogo:** Data curation, Software, Writing – review & editing. **Christoph Oberlack:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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Article V: Telecoupling visualizations through a network lens: a systematic review

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Synthesis

Telecoupling visualizations through a network lens: a systematic review

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ABSTRACT. Telecoupling is an integrative social-ecological framework that has made important contributions to understanding land change processes in a hyperconnected world. Visualizations are a powerful tool to communicate knowledge about telecoupling phenomena. However, little is known about current practices of telecoupling visualization and the challenges involved in visually displaying connections between multiple social-ecological systems. Our research takes stock of existing telecoupling visualizations and provides recommendations for improving current practices. We systematically review 118 visualizations presented in the scientific literature on telecoupling, and assess them in terms of their content and the adopted visualization approaches. To this end, we conceptualize telecoupling visualizations through a network lens. We find that they typically present networks of social-ecological systems, which are linked through flows. Displays of telecoupling connections through actor networks or action situation networks are less frequent. We categorize the existing visualizations into seven main types, which differ in terms of the visual encoding strategies used to represent telecoupling components. We then draw on insights from data visualization literature to reflect critically upon these current practices and provide practical recommendations. Finally, we show that network perspectives are inherent in telecoupling research and visualizations, and may deserve further attention in this field.

Key Words: *connectivity; data visualization; human-environment interactions; social-ecological systems; telecoupling; visual communication*

INTRODUCTION

Causes and consequences of land use changes are closely tied to distant places (Lambin and Meyfroidt 2011). The telecoupling framework aims to provide a holistic understanding of land use changes that captures distant linkages between social-ecological systems (Liu et al. 2013, Eakin et al. 2014). In recent years, there has been a boom in research on telecoupling phenomena, covering a wide range of subjects and bridging scientific efforts from various disciplines (Kapsar et al. 2019). Visualizations are a common means to depict, analyze, and communicate knowledge about telecoupled land systems (see, e.g., the telecoupling toolbox, Tonini and Liu 2017, McCord et al. 2018). They are particularly valuable and powerful in the context of intangible research subjects, e.g., those dealing with cross-scale issues or abstract concepts (McInerny et al. 2014). Visuals can support researchers in the process of exploring their data (Fox and Hendler 2011), helping them to unravel the human-environmental dynamics within and across systems. Furthermore, visual communication allows the sharing of knowledge in a more accessible, tangible, and memorable way than text sources (Rodriguez and Dimitrova 2011). It can thus facilitate cross-disciplinary exchange and coproduction of scientific knowledge, as well as communication with a nonscientific audience (Grainger et al. 2016). Despite their many advantages, visualizations also bear risks and limitations. All visual communications are selective in terms of the data they present or leave out (Tversky 2011). They can introduce biases through decontextualization or oversimplification of the subject, or through low quality data inputs (Dörk et al. 2013, Boehnert 2015). The production of informative and unbiased visualizations can thus be challenging, but also bring about fundamental gains for the generation and communication of scientific knowledge.

A telecoupling understanding of land use change implies the study of multiple social-ecological systems, and essentially the connections between them. Applying this more holistic lens to land use phenomena brings about particular visualization needs, which go beyond those commonly addressed in land system-based research, e.g., through land use maps. Despite these potential challenges and the important role of visualizations in telecoupling research, little systematic knowledge and guidance is available on existing visualization practices in this field. Addressing this knowledge gap is key to making full use of the potentials that visualizations can offer. Telecoupling research can thus benefit from a critical reflection of existing visualizations, including the contents they represent (or leave out) and the visualization approaches used to portray telecoupling dynamics. Therefore, the objective of this study is to provide insights into a better understanding of the current practices of telecoupling visualization. We further aim to identify key visualization challenges in this field and provide recommendations for improving current practice. We will do so by systematically reviewing visualizations presented in telecoupling publications and thereby drawing on insights from data visualization and network analysis literature.

MATERIALS AND METHODS

Key concepts and analytical framework

Data visualization, data representation, and visual encoding

Kirk (2016:19) defines data visualization as the "representation and presentation of data to facilitate understanding." This definition refers to two consecutive steps in the visualization process. Data representation is the process of converting data to graphical form. It defines the basic structure of the visualization and is shaped by the content that is to be visually displayed. Data presentation concerns more detailed design choices, e.g., on the use of color schemes or annotations (Kirk 2016). In this study,

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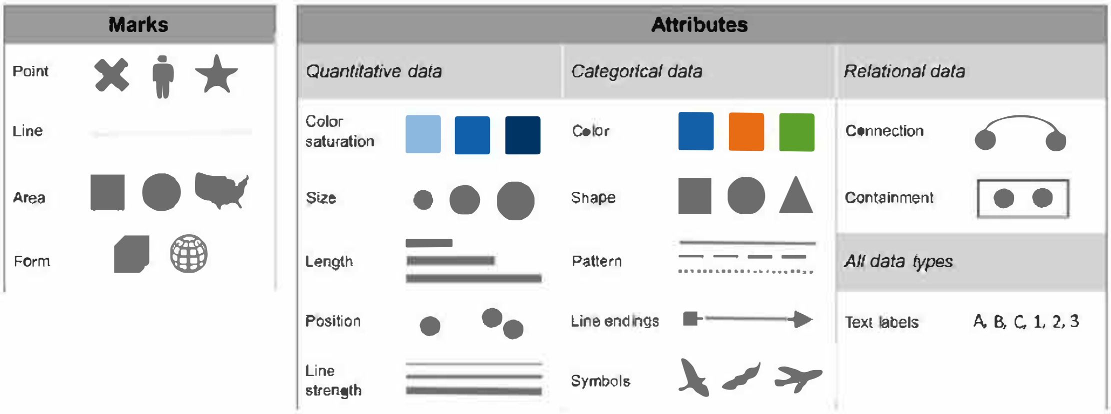
Fig. 1. A selection of visual mark and attribute encodings. Source: Authors, adapted from Iliinsky and Steele (2011) and Kirk (2016).



we focus on data representation, as we aim to gain insights into the way specific content, i.e., telecoupling information, is visualized.

A common approach to data representation is to select predefined visualization techniques such as bar charts or sankey diagrams to visualize the available data. A more elaborate approach is visual encoding (Kirk 2016, Healy 2018). It involves the translation of data into a combination of marks and attributes (see Fig. 1 for examples thereof). Marks include basic graphical elements such as points, lines, areas, or forms (Munzner 2014). Attributes (also called channels) define the appearance of marks, e.g., through color or size variations and respective labeling. For example, in a bar chart, the bars constitute the marks and the length of the bars the attributes. A large spectrum of attributes exist, as first outlined by Bertin (1983). Figure 1 presents a nonexhaustive list of visual attributes, with an indication of the related suitable data types (see Iliinsky and Steele 2011, Munzner 2014, Kirk 2016 for more options). Spatial data is an additional data type to consider, which is usually represented through spatially explicit marks, e.g., on maps.

Telecoupling: a network perspective

Several approaches to telecoupling analysis have been suggested (Friis et al. 2016). Liu et al. (2013) define telecoupling in terms of sending, receiving, and spillover systems that are connected through flows of material, information, and energy. Furthermore, they identify different system components, namely agents, causes, and effects. Other authors have further elaborated on this system-flow-based understanding of globalized land use phenomena by explicitly drawing attention to the role of governance structures and the underlying actor networks in a telecoupling context (Eakin et al. 2014, 2017, Lenschow et al. 2016, Oberlack et al. 2018, Munroe et al. 2019).

A network approach has been gaining prominence in telecoupling research (Seaquist et al. 2014, Prell et al. 2017, Schaffer-Smith et al. 2018, Andriamihaja et al. 2019), and areas of synergy have been proposed for network-related concepts and tools (Seaquist and Johansson 2019, Sayles et al. 2019). The basic components of networks are nodes and links. They can differ largely in terms of the content and the level of aggregation they represent (Bodin et al. 2019). Nodes can, for example, represent people in a social network or countries in a trade network. Similarly, links can indicate friendships between people or commodity flows between countries. In this sense, telecoupled phenomena can also be viewed as networks, for example, with social-ecological systems as nodes and flows as links (see Fig. 2). Nodes and links can thus

Fig. 2. (a) Node-link structure of networks. (b) Network examples: actor networks and networks of social-ecological systems. Source: Authors, inspired by Barabási (2016).

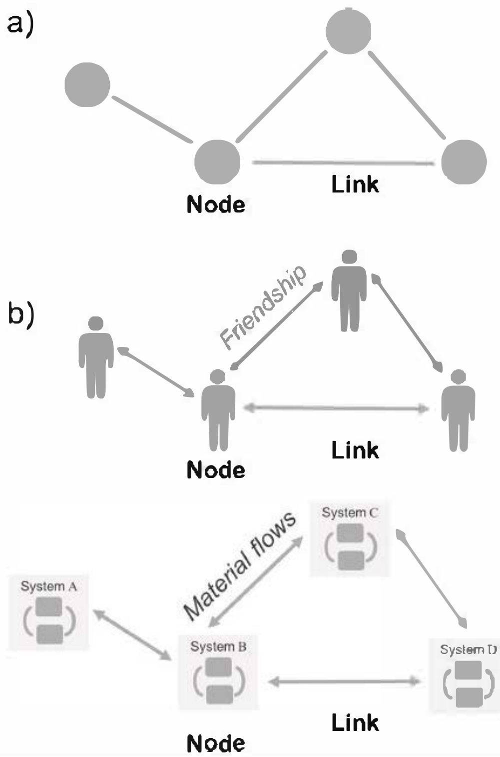


Fig. 3. Publication and case selection process.

Publication selection phase

Publication identification process	Publication search criteria	Results
• Web search in Scopus & Web of Science ○ Keyword search (in title, abstract, keywords): telecoupl* OR "tele-coupl*" ○ Date of search: April 8th 2019 • Manual search for additional publications: ○ Book chapters of telecoupling books ○ Source cross-check with other telecoupling literature reviews	• Publication date: January 2009 - present • Thematic focus: Telecoupling • Language: English	Web of Science: 104 publications Scopus: 111 publications Manual search: 22 publications **137 potential publications**, after duplicate check.
Publication selection process	**Publication selection criteria**	**Results**
• Screening of potential publications and publication exclusion according to criteria.	Exclusion criteria: • No visualizations present (13 excluded) • Main text body not in English (2 excluded) • Different use of telecoupling term (2 excluded)	**120 selected publications.**

Case (i.e. visualization) selection phase

Case identification process	Case identification criteria	Results
• Identification of all potential cases within the selected publications.	General rule: • Each figure presented in the selected publications (and labelled accordingly) classifies as one potential case. Exception: • If a figure contains multiple graphs that have different visual designs and fulfil the inclusion criteria below, they can be classified as separate cases (applied once)	**495 potential cases,** present in the 120 selected publications.
Case selection process	**Case selection criteria**	**Results**
• Content-scanning of all potential cases (incl. data collection on information presented in all potential cases) • Selection of cases based according to criteria.	Inclusion criteria: • Visualization content: telecoupling connections • Type of information visualized: empirical, case-specific information Exclusion criteria: • Duplication within source (9 excluded) • Duplication across sources (3 excluded)	**118 selected cases**, presented in **62 publications.**

represent an array of phenomena. Borgatti et al. (2009, 2018) identify four basic types of links in social networks: flows (e.g., information flows); interactions (e.g., collaborative activities), relations (e.g., power relations); and similarities (e.g., same gender).

Visualizing telecoupling networks

Visualizations are fundamental in network-based research, allowing viewers to detect patterns (Golbeck 2013) and "translate structural complexity into perceptible visual insights" (Lima 2011:79). Network visualizations differ in terms of how nodes and links are visually encoded, i.e., whether they are explicitly visualized through marks, or implicitly through attributes (Munzner 2014).

In this study, we adopt a network-based approach to analyzing visual representations of telecoupling dynamics. Hence, we interpret existing visualizations in terms of their node-link structure. We then identify the content that these nodes and links represent and assess how they are visually encoded through marks and attributes. This network-based approach presents a means to analyze telecoupling visualizations in a unified manner, independent of the definition of the system in use, displayed analytical units of the telecoupling framework, or scale of the study region.

Methods: systematic review of telecoupling visualizations

Publication and case selection

In this study, we systematically reviewed visualizations presented in telecoupling literature in order to investigate current practices of telecoupling visualization. We conducted the review in line with the guidelines of the Preferred Reporting Items for Systematic

Reviews and Meta-Analyses (PRISMA) statement (Moher et al. 2010). Figure 3 presents the publication and case selection process. In the first stage, we conducted a keyword search in bibliographic databases to identify scientific journal articles and book chapters on the topic of "telecoupling." We cross-checked these results with other systematic reviews of telecoupling literature (Carlson et al. 2018, Corbera et al. 2019, Kapsar et al. 2019). Taking specific exclusion criteria into account (see Fig. 3), we then selected 120 publications. They served as sources to identify potential cases for our study.

The second stage involved the selection of cases, i.e., visualizations. The selected articles and book chapters contained 495 visualizations, to which we applied the case identification, inclusion, and exclusion criteria shown in Figure 3. We found that 381 visualizations (77.0%) present empirical, case-specific information on real world phenomena. Moreover, 85 (17.2%) displayed purely conceptual information, typically portraying telecoupling frameworks. The remaining 29 visualizations presented other types of information, e.g., on methodological approaches. Of the 381 visualizations, 130 presented explicit information on telecoupling connections. These cases were considered for our review, making up 26.3% of the initially identified potential cases. We then excluded visualizations that represent similar content through an identical visual design. This resulted in the selection of 118 visualizations, i.e., cases, displayed in 62 publications (see Table A1.1 in Appendix 1 for a complete overview).

Coding process and data analysis

We employed an iterative process to develop the codebook. We first derived a preliminary version based on insights from telecoupling, network, and visualization literature. We then adjusted it throughout several rounds of coding, and recoded all cases using the final version of the codebook. It consisted of the following sections: general information; nodes; links; systems; flows; and data visualization (see Table A2.1 in Appendix 2 for the full codebook). In order to ensure the quality of the data, we applied sample-double coding. Of the cases, 33.1% were coded by at least two of the authors, which resulted in a percentage agreement intercoder reliability of 0.92.

We employed descriptive statistics to analyze the resulting data set. Furthermore, we developed a typology of telecoupling visualizations based on the characterization of single cases (Oberlack et al. 2019). The following visualization characteristics were thereby considered: visual encodings; and spatial explicitness of nodes and links. We used a truth table approach to identify the visualization types. A truth table presents the prevailing combinations of different case characteristics (Rihoux and Ragin 2009). Each unique combination of visualization characteristics corresponds to one visualization type.

Limitations

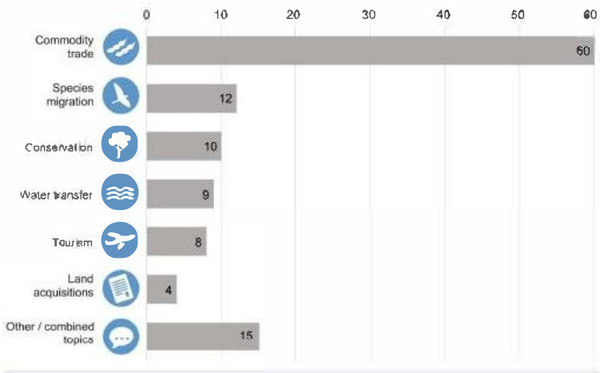
Our case selection was limited to those that explicitly refer to "telecoupling." This precludes consideration of the numerous other visualizations presenting information about telecoupling phenomena without mentioning the term. In addition, there appears to be a thematic bias in telecoupling visualizations, as the majority present information on commodity trade (see Fig. 4). It is clear that much can be learned from other thematic fields in terms of (alternative) visualization approaches used for displaying connections. However, by confining the scope of this study to telecoupling, we were able to systematically review all existing visualizations in this field and draw more reliable and concrete conclusions about its practice. Nonetheless, this specific focus also ruled out the inclusion of visualizations presented in grey literature and online visualizations. To our knowledge, no such sources exist that explicitly mention telecoupling and present visualizations that meet the case selection criteria of this study. However, because interactive visualizations offer important features for visualizing complex data sets, we further elaborate on them in the discussion section, based on illustrative examples. Finally, our approach of considering each visualization as a separate case poses two risks. First, this implies that multiple cases from the same article/book chapter can be included in the analysis. This may introduce a certain bias, if authors tend to use similar visualization approaches for multiple graphs in their articles. We introduced duplication exclusion criteria to limit this potential bias (see Fig. 3). Second, our approach bears the risk of neglecting the complementary function that multiple visualizations can have within one source. This aspect is also taken up in the discussion section.

RESULTS

Visualization content

The 118 reviewed visualizations covered a range of topics, most frequently commodity trade, species migration, and nature conservation (Fig. 4). They mainly display secondary data (n = 89), but also primary data (n = 5) or a mix of both (n = 8). For some cases (n = 16), no data sources were exposed.

Fig. 4. Telecoupling topics addressed in the selected 118 cases (by number of cases).

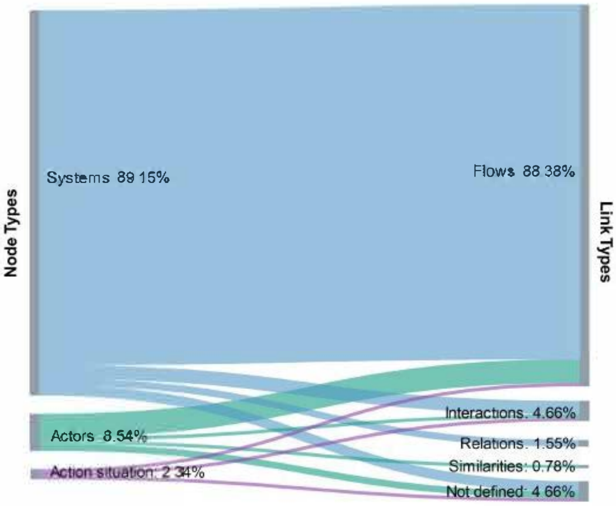


Nodes and links

We adopted a network lens to analyze telecoupling visualizations, identifying their node and link components and the content they represent. We found that they typically presented networks of social-ecological systems, which were linked through flows (Fig. 5). This is in line with the original framework of Liu et al. (2013), which proposes social-ecological systems and flows as main analytical units of telecouplings. Because of their predominance, a more detailed account of the use of systems and flows in telecoupling visualizations is given below.

Our analysis also revealed the presence of alternative node and link contents (Fig. 5). Besides systems, nodes also represent individual or collective actors, or action situations. Nine out of the 118 cases presented actors as nodes in a telecoupling network, without an explicit display of the systems in which the actors were embedded (see, for example, Gasparri et al. 2016, Tapia-Lewin et al. 2017). A small proportion of the reviewed cases (n = 2) displayed connections between action situations (Boillat et al. 2018, Oberlack et al. 2018). Action situations are decision arenas in which actors interact and take interdependent and joint decisions that lead to specific outcomes (Ostrom 2010).

Fig. 5. Node and link types represented in telecoupling visualizations and the combination thereof. Link types are based on Borgatti et al. (2009).

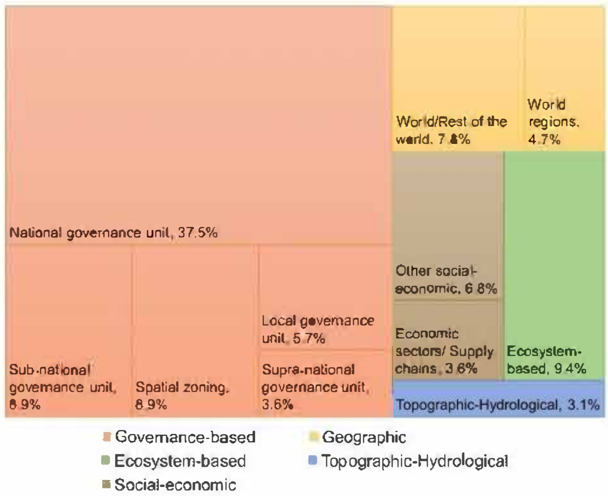


In some cases, telecoupling links represented interactions, relations, or similarities, rather than flows. Interactions refer to events that are facilitated through flows (Borgatti et al. 2018). Examples are market demand and supply interactions (e.g., Liu et al. 2015, Eakin et al. 2017) as well as collaboration and negotiation (Gasparri et al. 2016). Two cases also displayed relations, for instance referring to power or legitimacy (Chignell and Laituri 2016, Oberlack et al. 2018). One study (Andriamihaja et al. 2019) identified the presence of shared institutions as links between actors, thus indicating similarity between them. For some cases, the nature of the link was not specified.

Systems and flows

System nodes mainly differed in terms of three aspects: (1) whether a distinction was made between sending, receiving, and spillover systems; (2) whether they presented information about internal system dynamics; and (3) the way their boundaries were defined. We found that among all cases that presented system nodes, 31.3% made explicit reference to sending, receiving, and/or spillover systems. Furthermore, less than a third (28%) presented information about dynamics that took place within the respective systems. Some included specific information about the system components proposed by Liu et al (2013): actors (12.5%); causes (23.2%); and effects (17.9%). A range of system boundaries were used to delineate system nodes (Fig. 6). They were most commonly based on existing governance units, accounting for 64.6% of all identified system boundary types. Many thereby referred to administrative units at different levels (55.7%). Others pointed to spatial zonings (8.9%) such as protected areas or land concessions. System boundaries were further based on broader geobased characteristics (e.g., world regions, 12.5%), diverse social-economic features (e.g., economic sectors or infrastructure facilities, 10.4%), ecosystems (e.g., biomes or breeding sites of migrating species, 9.4%), or areas defined through their topographic-hydrological traits (e.g., watersheds or valleys, 3.1%).

Fig. 6. System boundaries used in telecoupling visualizations. System categories are partly based on Brondizio et al. (2016).



There was a tendency to define systems at a high level of aggregation. More than half of the identified boundary types (53.6%) represent telecoupled systems at the national level or above, i.e., systems defined through supra-national governance units, world regions, the rest of the world (in relation to a focal system), or the world itself. This often applied to spillover systems (see, for example, Liu et al. 2015, Parish et al. 2018). Furthermore, most boundary types (96.4%) provided an indication of the system's geographical location. Systems without a geographic reference were observed merely with regard to socioeconomically defined boundaries.

Flows in telecoupling visualizations mainly differed in terms of content. Material flows were most commonly depicted, accounting for 34.5% of all flow types identified. They generally referred to the export and import of goods, in particular agricultural commodities such as soybeans or beef. Some links also represented elements implicitly embedded within commodity flows. These can be virtual resources (5.1%) such as water or land, or virtual risks/benefits (7.3%) such as deforestation risks or biodiversity loss. The movement of capital (16.9%), humans (e.g., tourists, 12.4%), nonhuman beings (e.g., migrating birds, 10.2%), or information (9%) is also commonly visualized. Flows of ecosystem services are explicitly mentioned in a number of graphs (2.3%). Few cases displayed flows, but did not present any detailed information about their content (2.3%).

Fig. 7. Overview of visualization types used to display telecoupling dynamics, approaches used to represent node and link data, and their association with different visualization techniques (the order of the naming of the techniques corresponds to the order of the listed icons).

Visualization types	Data representation approaches				Visualization techniques	Visualization technique symbols
	Nodes		Links			
	How are nodes visually encoded?	*Are nodes spatially explicit?*	*How are links visually encoded?*	*Are links spatially explicit?*		
Relational graphs	Mark	X	Mark	X	Schematic diagrams, Network diagrams, Chord diagrams	
Quantity graphs	Link attribute	X	Mark	X	Bar charts, Line graphs, Area graphs, Box plots	
Route maps	Mark	✓	Mark	✓	Route maps	
Link maps	Mark	✓	Mark	X	Flow maps, Connection maps	
Quantity maps	Mark	✓	Node attribute	X	Choropleth maps, Proportional symbol maps	
Quantity maps with link marks (hybrid)	Mark	✓	Node attribute & Mark	X	Combination of Quantity maps and Link maps	
Partially spatial relational graphs (hybrid)	Mark	✓&X	Mark	X	Combination of Schematic diagrams and various map types	

Visualization approaches

Visualization types

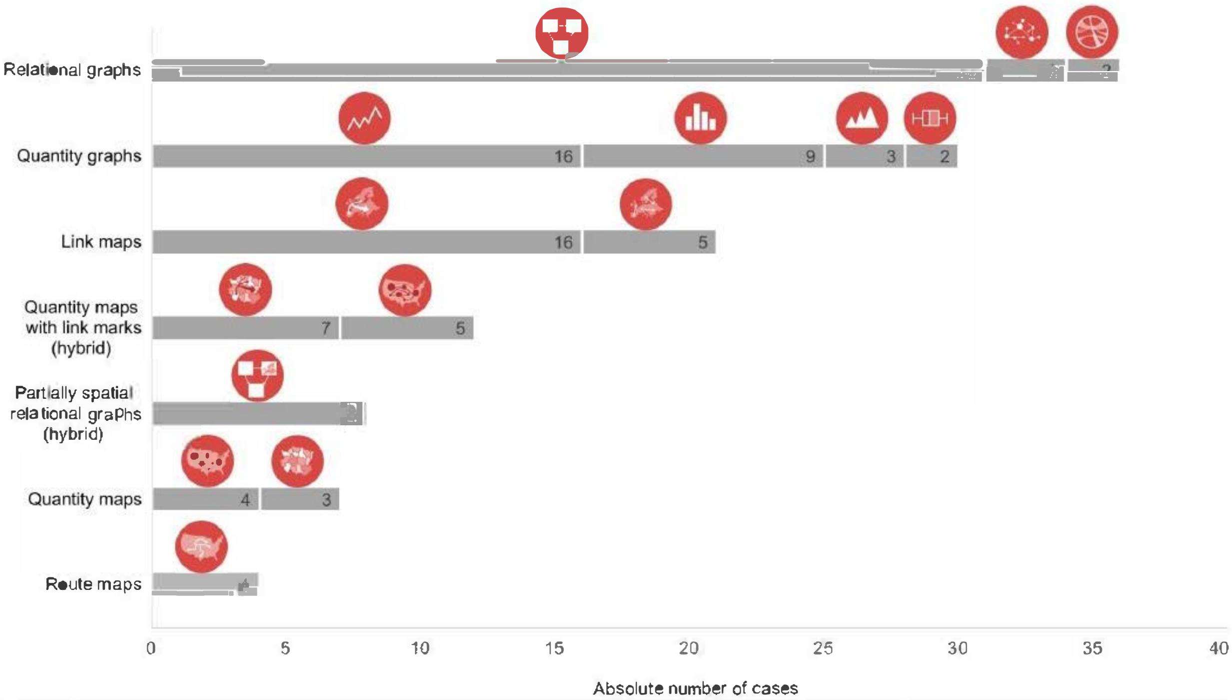
Our analysis identified seven distinctly different telecoupling visualization types used in current practice, which correspond to 15 visualization techniques (see Fig. 7). They reflect unique combinations of data representation strategies used to depict node and link information visually.

Relational graphs and *quantity graphs* are the two most frequently used telecoupling visualization types (Fig. 8). Of all cases, 55.9% made use of one of these two types. Neither are spatially explicit. For *relational graphs* (n = 36 out of 118 cases), the predominant visualization technique used was schematic diagrams. In many instances, these were box and arrow diagrams that reproduced the telecoupling framework structure proposed by Liu et al. (2013) and applied it to an empirical context. Chord and network diagrams are alternative but much less frequently used forms of *relational graphs*. *Quantity graphs* (n = 30) include a number of different visualization techniques used to display quantitative, comparative data. Examples are different types of bar charts and area graphs. In these visualizations, nodes are not explicitly depicted through a mark, but rather implicitly through a link attribute.

In 44.1% of all cases, nodes were depicted with a spatial reference. However, only 3.4% also presented links in a spatially explicit way. This is the case for *route maps* (n = 4), which present links as a series of geographical data, thus depicting a path from one location to another. *Link maps* (n = 21) depict links as geodesic lines instead, either as connection maps or flow maps. The former present nodes through points on a map, and the latter through areas. *Quantity maps* (n = 7) do not explicitly present link connections. They indicate the presence of links by presenting quantitative link information as attributes of geospatially explicit nodes. For instance, the proportional symbol map presented by Parish et al. (2018) displays information about the magnitude of wood pellet exports (links) through the varying size of the bubbles representing the ports (nodes) from which these goods are shipped. Furthermore, we have identified hybrid types that combine multiple visualization approaches, for instance by overlapping choropleth maps and flow maps (see, for example, Kastner et al. 2015).

The identified visualization types can be used to depict node and link information, irrespective of their thematic content. Each of them can thus be applied to a variety of telecoupling phenomena. This is underlined by our results, which show a high diversity in visualization types used for different telecoupling topics (see Fig. 9). Exceptions are visualizations of land acquisition telecouplings (though this is possibly linked to the small n for this category) and those of species migration (showing a relatively large share of *link maps*). Each of the visualization types has its own set of data requirements. Depending on the topic, such data might be more or less accessible. For example, a *route map* can in principle

Fig. 8. Frequency of visualization types by occurrence in cases (n = 118), with an indication of their composition of visualization techniques (see Fig. 7 for the meaning of the icons).



be used to present any type of flows between two places, e.g., flows of water, migrating species, or conservation funds. However, it requires spatially explicit information about the flow route. Accessing such information might be particularly challenging for some types of flows, e.g., species migration routes, but relatively more straight forward for others, e.g., water transfer channel infrastructure (see, for example, Quan et al. 2016).

Visual attributes

The identified visualization types indicate different approaches for visually representing the two key components of telecoupling visualizations, i.e., nodes and links. Moreover, visual attributes can be applied to node and link marks, in order to present additional or more detailed information about the telecoupling phenomena (cf. Fig. 1).

In Appendix 3, we provide an overview of the main visual attributes used in existing telecoupling visualizations, based on illustrative case examples (see Figure A3.1). A large range of attributes was used, providing different types of information. For instance, authors use visual attributes to characterize nodes, e.g., distinguishing between export and import countries, and to delineate them, e.g., indicating closed or porous system boundaries. Visual attributes are also used to indicate the direction, magnitude, or other characteristics of the displayed links. For instance, when portraying the flows linked to the expansion of banana plantations in Laos, Friis and Nielsen (2017*a*) apply color attributes to the link marks (i.e., the arrows representing flows) to add information about flow content (e.g., discursive flows or political flows). They also use solid and dashed arrows to indicate whether or not these arrows represent spillover flows.

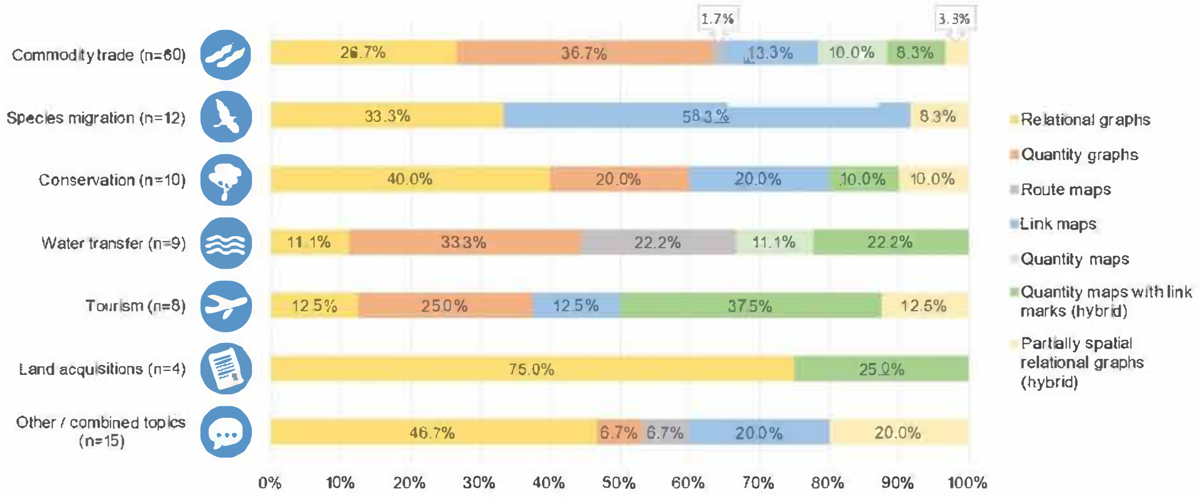
Visual attributes were also used to display temporal information, in particular to present comparative data over time. This applied to 24.6% of all cases (n = 30). The majority thereby presented temporal variations in quantitative data (n = 26), such as the changing magnitude of commodity exports (see, e.g., Reenberg and Fenger 2011). *Quantity graphs* are the predominant visualization type used to present such information, using positioning attributes in reference to a time scale (see, e.g., Yang et al. 2016). *Quantity maps* allow to present quantitative information that is both temporally and spatially explicit. In a choropleth map, for instance, color attributes can be used to show net changes of flow magnitude across a certain time period (see Marston and Konar 2017). Four cases further present qualitative data in a temporally explicit framing, e.g., through labelling (Eakin et al. 2017) or positioning on a time line (Raya Rey et al. 2017).

DISCUSSION AND CONCLUSIONS

Data representation in telecoupling visualizations: current practices, challenges, and recommendations

Our study shows that visualizations are widely used in communicating knowledge about telecoupled connections, and that this practice is rich in content and visual diversity. In particular, we draw attention to the node-link structure of

Fig. 9. Relative frequency of use of visualization types for each telecoupling topic.



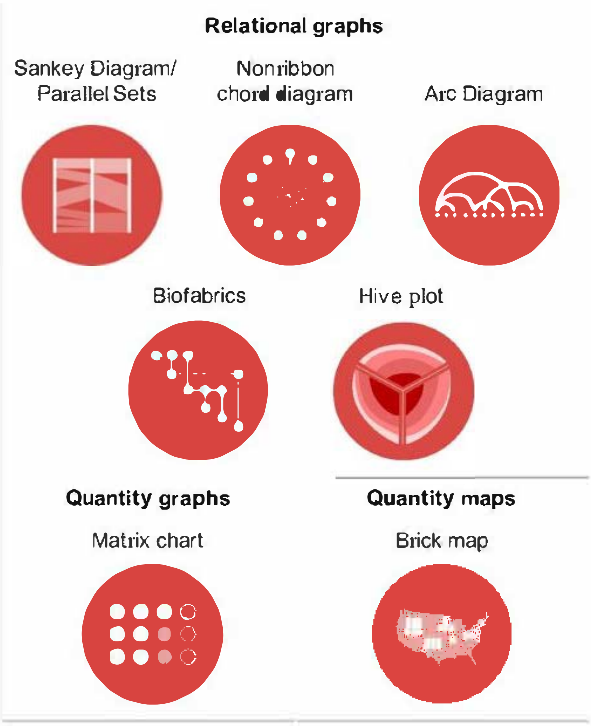
telecoupling visualizations and unravel the visual encoding strategies applied to them. We find that the visual representation of telecoupling phenomena is particularly challenging, given the multidisciplinary conceptual foundations, diversity of analytical approaches, and richness of the data used in this field. In this section, we reflect upon selected practices of data representation in telecoupling visualizations, providing specific recommendations for enhancement. We thereby refer to the two concurrent data representation processes: visual encoding; and the selection of visualization techniques.

Our research identified seven telecoupling visualization types. These differ in terms of the way node and link information is visually encoded, i.e., explicitly through visual marks or implicitly through visual attributes. In *relational graphs*, *route maps*, and *link maps*, nodes and links are shown explicitly and can thus be quickly captured by the target audience. In *quantity maps* and *quantity graphs*, either node or link information is implicitly encoded. This facilitates the visually display of quantitative data, but also makes the implicitly presented information less accessible to the viewer. *Quantity maps with link marks (hybrid type)* attempt to address this issue, for example by displaying selected links in the form of arrows, in addition to the presentation of link information through visual attributes (e.g., color coding in a choropleth map). However, this approach implies that links are encoded in multiple ways, which may lead to visual clutter and encoding inconsistencies. These examples illustrate that several potentially competing factors (number of data points, combination of data types, coding consistency, etc.) affect visual encoding decisions. Careful reflection and design is thus needed at this stage of the data visualization process, ensuring that the selected visual encodings facilitate a rapid and intuitive decoding process (Iliinsky and Steele 2011) and support the main purpose of the visualization (Kirk 2016).

The same applies to the selection of visual attributes. Our research revealed that telecoupling visualizations commonly make use of (combinations of) visual attributes to represent different telecoupling contents. The field could learn from data visualization literature, which discusses a broad range of different attributes and presents guidance on their selection and implementation. Iliinsky and Steele (2011), for instance, present an overview of attributes and indicate their suitability for different data types and the number of distinct values they can represent. Munzner (2014) provides an effectiveness ranking for different visual attributes. Once attributes are selected, their implementation also requires careful consideration, e.g., appropriate color scheme (see, for example, Brewer 1994, Borland and Taylor 2007) or axis ranges (Tufte 2006). A range of literature presents and critically discusses recommendations in this respect (see, for example, Kelleher and Wagener 2011, Kosara 2016, Healy 2018).

Regarding the selection of visualization techniques, our research revealed some diversity in existing telecoupling visualizations, with 15 different techniques being used. The field of data visualization, however, offers a wider range of visualization techniques. Multiple online catalogues exist that group them by function (see, e.g., the Data Visualization Catalogue (https://datavizcatalogue.com/search.html) and the R Graph Gallery (https://www.r-graph-gallery.com/), data input (From Data to Viz web site (https://www.data-to-viz.com/), or both (Data Viz Project, https://datavizproject.com/). Figure 10 presents a selection of techniques that were not identified in the cases but could provide interesting opportunities to display telecoupling phenomena. Some form the basis of well-known interactive visualizations on land-related themes, such as the sankey diagram used in the Trase platform (SEI and Global Canopy 2020) and the nonribbon chord diagram presented on the Land matrix platform (ILC et al. 2019). Matrix-based charts (Ghoniem et al. 2005), hive diagrams (Krzywinski et al. 2012), and biofabrics (Longabaugh 2012) are alternatives to node-link diagrams, which aim to address the challenge of visual clutter in large and dense networks[1]. The edge bundling technique, involving the visual bundling of adjacent links, can also be helpful in this respect. It is commonly applied to chord diagrams (Holten 2006) or *link maps* (Holten and Van Wijk 2009, Lambert et al. 2010). Finally, brick maps present an alternative technique for *quantity maps* (Few, 2013). They portray spatially explicit, quantitative values through an accumulation of squares representing a specific value range. Few (2013) suggests that this approach could be more effective in terms of visual perception than the use of varying colors (as in choropleth maps) or bubble sizes (as in proportional symbol maps).

Fig. 10. Selection of additional visualization techniques suitable for the visualization of telecoupling connections, grouped by the visualization types.



Integrating multiple perspectives: a telecoupling visualization challenge

A combination of different views is essential for achieving a sound understanding of social-ecological phenomena (Berkes et al. 2003), particularly in a hyperconnected world. Nonetheless, in order to produce purposeful results, researchers may need to choose between different entry points and analytical foci on the subject matter. A similar challenge exists in presenting research visually. Visualizations can display single or multiple perspectives of the portrayed subject, accounting for different levels of complexity (Kirk 2016). Lima (2011) identifies three main perspectives in network visualizations: (1) a micro perspective providing detailed information on specific network entities; (2) a relationship perspective focusing more on dismantling network links and presenting analytics thereof; and (3) a macro perspective presenting a bird's eye view of the network and offering insights on its topology. Many of the reviewed cases seem to emphasize one of these perspectives, respectively: (1) providing a detailed characterization of social-ecological systems and their internal dynamics but presenting limited information on the flows connecting them (e.g., Chignell and Laituri 2016, Hulina et al. 2017); (2) identifying and characterizing the links in telecoupled connections (e.g., Reenberg and Fenger 2011, Schierhorn et al. 2016); (3) displaying large telecoupled networks while presenting less detail about individual nodes and links (e.g., Prell et al. 2017, Andriamihaja et al. 2019).

The data visualization process thus requires and is guided by choices on the perspectives and levels of details that are to be visually presented. The following case examples illustrate how the identified visualization types (cf. Fig. 7) allow for different presentations of commodity trade phenomena, the most frequently visualized telecoupling topic (cf. Fig. 4). *Quantity graphs* are commonly used to display highly aggregated trade data, thus presenting a relationship view between trade partners (e.g., Schierhorn et al. 2016). *Quantity maps* and *link maps* add a spatial component to this, potentially revealing spatial trade patterns (e.g., Liu 2014). *Route maps* present more detailed spatial information by displaying the precise transport routes and mapping the multiple sites, e.g., cities or ports, that the commodities pass through (e.g., Godar and Gardner 2019). This allows a better understanding of such telecoupling phenomena, for example by indicating potential spillover sites or the different actors involved along the route. *Relational graphs* can have multiple uses. For example, schematic diagrams are commonly used to map existing trade phenomena in terms of the telecoupling schema and present micro views on internal system dynamics (e. g., Garrett and Rueda 2019). Network and chord diagrams depict trade networks from a more macro perspective (e.g., Xiong et al. 2018). They can provide insights on the structure of a trade network, for example by highlighting predominant trade relationships or showing clusters among trade partners.

The more perspectives combined, the more challenging it is to accommodate them in a single visualization (Munzner 2014). Visually portraying telecoupling phenomena while avoiding both an oversimplification of the complex subject matter and an overloading of the visualization is thus a key challenge in this field. It is essential for researchers first to reflect on all potential perspectives that could be combined, and then to select with care just enough perspectives to represent the telecoupling phenomenon adequately and purposefully. Once a selection is made, different approaches can be used to simultaneously portray multiple perspectives in a visual form. Hybrid visualization techniques, for instance, can be used for joint display of multiple types of information (see hybrid types, Fig. 7). However, they may be challenging and time-consuming to decode if not carefully designed. Text boxes and labels within visualizations can also be a helpful means to provide contextual information (see, e.g., Godar and Gardner 2019). Furthermore, data can be juxtaposed and presented across separate visual objects (Gleicher et al. 2011). Thereby, data comparison can be facilitated through side-by-side presentation of the same chart types presenting different subsamples of a dataset (see the small multiples technique, Tufte 2001). An alternative is using multiple graphs of different design to present complementary data (Munzner 2014). For example, Liu et al. (2018) complement a flow map on soybean trade with more specific information through additional bar charts. Data can further be visualized through multiple, superimposed layers (Gleicher et al. 2011). López-Hoffman et al. (2017), for instance, present a schematic representation of bird migration with a background map that provides additional geographic context about these systems. Finally, comparative data can be combined in a visualization through explicit encodings that compute the relationship between objects (Gleicher et al. 2011). Sun et al. (2018), for instance, indicate net imports of soy using a color scale.

Interactive visualizations

Interactive visualizations offer far greater possibilities to represent multiple aspects of telecouplings than static ones. Interactive features can enable users to navigate between different scales and perspectives, tailoring the visual display to their needs and interest (Bostrom et al. 2008, Janvrin et al. 2014). They allow them to engage actively with the data, and possibly analyze and download it. The following examples of interactive visualizations on commodity trade illustrate a few of the many potential benefits of using interactivity in this field. The interactive flow map Resourcetrade.earth (Chatham House 2018) presents elaborate possibilities for users to define the level of analysis shown in the visualization. Through data filtering processes, they can choose among different types of flows at varying levels of aggregation (commodity [sub]types). On the trase platform (SEI and Global Canopy 2020), commodity production data is presented in a spatially explicit way and also interactively linked to other supply chain stages. Users have various options to customize the data display, e.g., by applying different scales to the commodity production data (municipality, biome, country, logistic hubs). On the Economic Complexity Observatory web site (Simoes and Hidalgo 2011, CID 2020*a*), users can also choose different visualization techniques to display the same trade data. This feature helps to address the needs of different users (Spiegelhalter et al. 2011). Furthermore, interactive features can allow users to explore data in a three-dimensional space (see, for example, the Globe of Economic Complexity, Cornec and Vuillemot 2015, CID 2020*b*). They also offer interesting opportunities to present longitudinal data, for instance through time sliders or movies (Moody et al. 2005). This is particularly relevant to this field, given its spatio-temporal dynamics. As we have shown, a temporal angle is often missing in telecoupling visualizations.

However, interactive graphs also bring about challenges. Their development and maintenance can be demanding in terms of resources. Furthermore, their use requires computer literacy and potentially more refined user skills, preventing some potential users from accessing the displayed information (Spiegelhalter et al. 2011). Visualization developers have a high responsibility to ensure the legitimacy and validity of the data that is visualized and can potentially be downloaded by users. In terms of design, the web interface needs to allow users to navigate intuitively between different levels of analysis. Shneiderman's renowned mantra "overview first, zoom and filter, details on demand" (1996:337) can be helpful in this respect, along with other techniques proposed to reduce intricacy in multiperspective visualizations (Lima 2011).

Hence, although static visualizations are and will remain important tools for scientific communication, interactive graphs and dashboards present novel opportunities to accommodate the multiplicity of perspectives often present in telecoupling research. Because visual encodings, i.e., marks and attributes, also form the basis of interactive graphs, the insights and recommendations proposed in this study are equally relevant to this form of visualization. Though falling outside of the scope of this analysis, alternative mediums for cocreating and communicating scientific knowledge, e.g., videos, participatory mapping and art, and augmented and virtual reality, may further be explored, as they offer other stimulating ways to engage with the target audience and knowledge holders.

Reflecting the content of telecoupling visualizations: system boundaries and actor dynamics

Visualizations are simplifications of a complex reality, and thus naturally emphasize certain elements and perspectives while leaving others out. They are a representation of researchers' mental models of the phenomena they are investigating. In this study, we have analyzed the content of telecoupling visualizations, offering a glimpse into current telecoupling research practice and the underlying choices that go with it. Here, we discuss and reflect on selected findings that reveal how certain perspectives and telecoupling components receive dissimilar attention in telecoupling visualizations. We thereby focus on the results regarding the presence of system boundaries and actor dynamics.

The definition of system boundaries has been put forward as a critical issue in telecoupling research (Friis et al. 2016, Friis and Nielsen 2017*b*). In visualizations, where systems are often clearly delineated, researchers' boundary choices are highly visible. Our study reveals that in telecoupling visualizations, systems are often defined at a high level of aggregation (country level and above) and commonly based on territorial governance structures. These results are in line with previous claims suggesting that system boundaries in telecoupling research are predominantly territory-based (Friis and Nielsen 2017*b*) and frequently delineated at country level (Seaquist and Johansson 2019). Although data availability issues may also play a role in this, e.g., trade data often being recorded at national level, these results may indicate that certain systemic perspectives and scales of analysis are predominant in telecoupling research. By all accounts, they call for a careful selection and (visual) communication of system boundaries, which includes a critical reflection on the potential gains and limitations that different perspectives may bring.

Furthermore, we have shown that system boundaries are usually drawn based on one or more specific characteristics of real world phenomena, e.g., hydrological-topographic. A social-ecological system approach, however, postulates the consideration and integration of multiple dimensions or subsystems within one geographic area (Ostrom 2009). In empirically-based visualizations, it can be challenging to present this multidimensionality and multiplicity of (sub)systems visually because of their limited capacity to portray manifold perspectives (as outlined in the previous section). Brondizio et al. (2016) address this challenge by visually displaying multiple layers of one geographic area, each showing different subsystems of the social-ecological system. Others make use of nested views to present multiple systems of varied scales conjointly (Drakou et al. 2017).

Our analysis further reveals that actors and the interactions between them are given relatively little emphasis in the reviewed cases. Though present in visualizations of actor networks and action situation networks, we have found that actor-specific information is less frequently represented in visualizations showing connections between systems, i.e., as elements within the systems. A recent systematic review of telecoupling literature presents similar observations, suggesting that actors and their interactions deserve further attention in telecoupling research (Kapsar et al. 2019). In terms of explaining their visual absence from telecoupling visualizations, additional factors may play a role. For example, actor-related information may be particularly challenging to capture visually and accommodate within telecoupling visualizations. Similarly, disciplines that place more emphasis on actor perspectives may make less use of visualizations. However, considering the importance of actor dynamics for understanding and governing telecoupling processes (Liu et al. 2013, Eakin et al. 2014, Munroe et al. 2019), it is important to develop effective visualizations that capture these components.

These reflections show that, on the one hand, the decisions that researchers make during the visualization design process are shaped by their ability to visualize certain research contents. On the other hand, they are also intrinsically guided by their view of the telecoupling phenomenon and the selected approach to investigating it. Do we present a micro, macro, or link perspective of the telecoupling phenomenon, or a combination thereof? How do we define our system boundaries? Do we consider spillover dynamics? And do we take temporal dimensions into account? These and many more choices define research directions and the way we communicate about them, leading to different, complementary understandings and visual presentations of telecoupling connections. In this regard, the visualization process offers researchers an opportunity to reflect upon the underlying assumptions and perspectives that define their research, and to communicate them in a transparent way.

The potential of network perspectives

This study demonstrates the ubiquity of network perspectives in telecoupling visualizations, even if networks are often not explicitly discussed. Such a networked view of telecoupling is inherent in its definition, as the framework is built on the idea of connectivity. Nonetheless, visual depictions of telecoupling dynamics often do not appear to go beyond the display of broader large-scale flows between systems whose boundaries are typically defined based on administrative units at high levels of aggregation. The contexts, drivers, and actors operating across these systems are thus often not visually captured at the levels at which decisions are made. However, our research also underpins alternative avenues for portraying telecoupling phenomena, namely through actor networks and action situation networks. These approaches allow for the depiction of telecoupling connections that span geographical locations and scales and emphasize the actors driving these dynamics and their interrelations. Furthermore, by introducing insights from the field of social network analysis, we have pointed to additional ways of conceptualizing links in telecoupling, i.e., as interactions, relations, or similarities. These can complement the predominant flow-based perspective and may be useful for exploring more intangible linkages, e.g., values, power relations, or political dynamics, that are increasingly considered as crucial for governing telecoupled processes (Eakin et al. 2017). These insights support previous calls for the further integration of network-based views, concepts, and methods in telecoupling research (Sayles et al. 2019, Seaquist and Johansson 2019). This may provide for more in-depth understandings of the relations that drive and shape telecoupling connections, as well as the broader network structure of telecoupled social-ecological systems. Particularly if paired with effective visuals, network-based understandings of telecoupling phenomena may thus offer promising new directions for identifying and communicating the main leverage points for addressing global sustainability challenges within local realities.

[1]See also R. Kosara, blog, https://eagereyes.org/techniques/graphs-hairball#more-1685

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/11830

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Data Availability:

The data that support the findings of this study are openly available in Bern Open Repository and Information System (BORIS) at https://doi.org/10.7892/boris.141116.

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Article VI: Fostering sustainable agriculture beyond farm level: entry points and barriers for voluntary sustainability standards

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Status: Submitted

Fostering sustainable agriculture beyond the farm level: entry points and barriers for voluntary sustainability standards

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Abstract

The efficacy of Voluntary Sustainability Standards (VSS) can be reinforced or undermined by spillovers affecting sustainability beyond the farm level. This calls for their consideration in VSS systems. Recent aspirations of VSS schemes for positive impact beyond scale present promising opportunities in this direction. However, limited knowledge exists regarding the nature, range, and effectiveness of such initiatives. This study identifies and critically discusses entry points and barriers for integrating spillover perspectives in VSS systems, drawing on interviews with VSS experts and empirical evidence on 69 agricultural standards. We find that VSS systems can address spillovers through their certification-based activities, but also other engagements such as landscape initiatives. However, their potential to do so is underutilized in practice due to significant (structural) barriers. These barriers highlight the importance of incorporating spillovers in strategic priority-setting within VSS systems, taking targeted actions at operational levels and employing complementary measures across different governance interventions.

Keywords: certification, eco-labels, environmental governance, spillovers, telecoupling

Introduction

Voluntary Sustainability Standards (VSS) are private, market-based governance instruments that have emerged as a response to pressing challenges driven by agricultural land use, including the biodiversity crisis, climate change, human rights violations, and child labor (Lambin *et al.* 2014; Meemken *et al.* 2021). VSS systems define rules, principles, and criteria for sustainable agriculture; these outline the actions that producers and other value chain actors need to take to be certified (Milder *et al.* 2015; Tayleur *et al.* 2017). The potential of VSS to reduce negative impacts of agricultural land use, however, can be undermined or reinforced through spillovers that affect sustainability beyond the farm level (Heilmayr et al., 2020). Spillovers can cause spatial scale mismatches in VSS design, whereas the sustainability implications of agricultural land use expand beyond their primary level of intervention, such as the farm or plot level (Coenen et al, 2023). This can occur in different ways. First, agricultural practices can trigger socio-economic and environmental spillover processes that have sustainability implications in near or distant locations (Meyfroidt et al., 2020, 2010). Examples include processes of pesticide drift (Cech *et al.* 2023; Linhart *et al.* 2019; Zaller *et al.* 2022), migrant worker remittances (Dey, 2022; Kapri and Ghimire, 2020), and the transmission of farming knowledge and norms through social networks (Albizua *et al.* 2021; Junquera & Grêt-Regamey 2019). VSS can regulate these spillovers to different extents (Sonderegger *et al.* 2022). Second, VSS are governance interventions; their adoption and implementation can have impacts beyond the certified production unit (Meyfroidt *et al.* 2020, 2018; Smith *et al.* 2019). For instance, the presence of an organic farm can positively affect the adoption of sustainable practices in nearby farms (Läpple & Kelley 2015; Lewis *et al.* 2011). Price premiums received for certified products can also be used for community development programs (Fairtrade International 2022; Snider *et al.* 2017).

Various studies highlight the importance of considering such spillovers in VSS content and design, as well as their impact assessments (Bastos Lima *et al.* 2019; Heilmayr *et al.* 2020; Meemken *et al.* 2021;

Schmitz-Hoffman *et al.* 2014). Correspondingly, landscape and jurisdictional approaches are gaining momentum (Scherr *et al.* 2017; UNDP 2019). These are key approaches through which the VSS community aspires to develop new strategies for promoting sustainability, not only at production level (e.g., farms), but also within wider landscapes (ISEAL Alliance 2017; Mallet *et al.* 2016). However, spillovers of agricultural land-use may go beyond farm and landscape levels. Examples include species movements, remittances, and knowledge diffusion (Sonderegger *et al.* 2022). Therefore, both farm- and landscape-level approaches may face challenges in integrating spillover dynamics in a comprehensive way.

There is limited knowledge about the strategies that standard-setting organizations can use to integrate spillover perspectives into their VSS systems. Existing knowledge merely points to particular measures, such as the explicit consideration of unintended effects in the theory of change of standards (Oya *et al.* 2018), the presence of spillover-relevant requirements in the standard documents (Kissinger *et al.* 2015; Sonderegger *et al.* 2022; Tscharntke *et al.* 2015), and certification at landscape or jurisdictional level (Deans *et al.* 2018; Meyfroidt *et al.* 2010). These knowledge gaps require comprehensive assessments of the strategies that VSS can use to foster sustainability beyond the farm level, as well as their challenges. In addition, science-policy dialogues are needed to support the ongoing developments in the VSS community. This study aims to respond to these gaps by addressing the following questions: Which entry points in VSS systems account for and address the spillovers related to agricultural VSS? What are the barriers to implementing them?

The article is structured as follows. After introducing the methods (Section 2), we conceptualize spillovers in the context of agricultural VSS (Section 3) and introduce different domains of VSS systems (Section 4). In Section 5, we introduce key entry points for integrating spillover perspectives into the different domains of VSS systems. We link them to good practice guidelines proposed by the International Social and Environmental Accreditation and Labelling (ISEAL) Alliance and illustrate current practice with empirical evidence based on an analysis of the ITC Standards Map database, as well as key informant interviews with standard-setting and VSS organizations. Furthermore, we critically discuss barriers to the entry points (Section 6). Finally, we provide reflections on the overall potential of VSS systems to foster sustainability beyond the farm level (Chapter 7).

Methods

This study is based on: 1) a review of scientific and grey literature on VSS and transnational governance; 2) 15 semi-structured key informant interviews with standard-setting organizations and expert bodies on VSS; and 3) analyses of VSS data from the ITC Standards Map database. The interviews were conducted between July 2021 and April 2022. We applied visual elicitation methods, using visuals to inform, structure, and stimulate the interview discussion (Bagnoli 2009; Bravington & King 2018; Buckley & Waring 2013; Crilly *et al.* 2006; Salmons 2016). During the interviews, we used Figure 1 to illuminate the concepts presented and Figures 2 and 3 to support the identification of potential entry points and barriers in VSS systems for governing spillovers. These visual stimuli were continuously developed based on interview inputs (Crilly *et al.* 2006). We coded the interview data with NVIVO, using a coding scheme derived from the contents of the respective graphics.

We provide evidence from the ITC Standards Map database (https://standardsmap.org/) to illustrate current VSS practice (ITC 2023). We present this data using a sample of 69 agricultural VSS, which we selected based on criteria regarding content (focus on agricultural products, primary production stage, and sustainability), standard implementation (presence of a conformity assessment system), standard actuality, and data availability (see Annex for a list of the selected VSS). Furthermore, we used and further developed the dataset of Sonderegger *et al.* (2022) to provide more detailed insights into the way standard requirements regulate spillovers (see Figure 6 in Section 5.3.1). Our analysis is based on categories of VSS requirements, as used by the ITC Standards Map to map the contents of VSS. We identified and coded 214 requirement categories relevant to spillovers of agricultural land use (based on Sonderegger *et al.* 2022) in terms of their targeted spillover components (i.e. trigger, process, or impact).

Spillovers in the context of agricultural VSS

The concept of 'spillovers' is widely used to discuss cross-scalar socio-economic and environmental processes and their sustainability effects (Lewison *et al.* 2019; Liu *et al.* 2018, 2013; Meyfroidt *et al.* 2020). This study focuses on spillovers relevant to the context of agricultural land use and VSS, in line with our aim to identify entry points and barriers when accounting for such spillovers in VSS systems. We distinguish between three types (see Figure 1 and Table 1 for further elaborations and examples): 1) spillovers of agricultural land use; 2) supply chain spillovers; and 3) spillovers of VSS adoption and implementation.

First, spillovers of agricultural land use refer to processes triggered by agricultural land use activities, leading to positive or negative sustainability impacts outside of the farm. Sonderegger *et al.* (2022) present a non-exhaustive overview of 21 types of such environmental and socio-economic spillovers. They can occur independently from any regulation by VSS. However, they can also be addressed by VSS, for instance through respective provisions in standard documents. Second, supply chain spillovers refer to processes along the supply chain that affect sustainability in near or distant places outside the farm (Barbieri *et al.* 2021; Liu *et al.* 2018; Xiong *et al.* 2018). An example is pollution at the processing stage of the supply chain. These spillovers can occur independently of whether or not the respective products are certified. Third, spillovers of VSS adoption and implementation occur *because of* a standard, affecting sustainability beyond the certified farms. For example, certification activities can affect local and national food security (Oosterveer *et al.* 2014). Such processes are also termed "leakages", a subset of the spillover concept referring to the displacement of impacts caused by governance interventions (Bastos Lima *et al.* 2019). In VSS literature, the resulting impacts are also referred to as indirect, secondary, or systemic impacts of VSS (Ruben 2017; Steering Committee 2012; WWF *et al.* 2018).

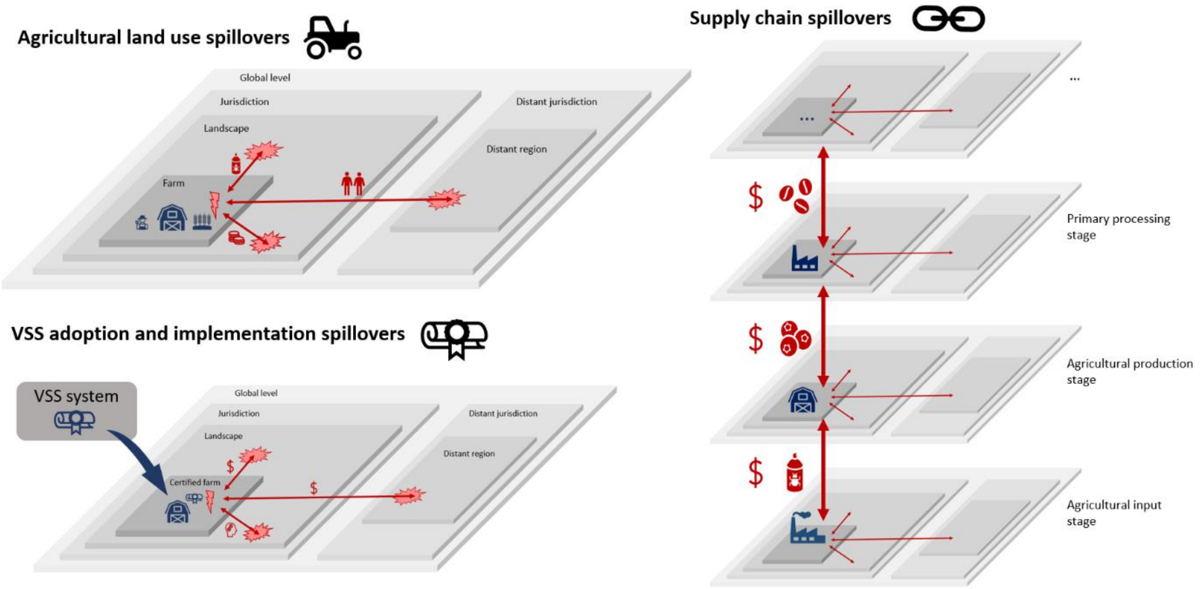

Figure 1: Three types of spillovers in the context of agricultural VSS**.** Source: Authors, based on Sonderegger *et al.* (2022).

Spillover type	Link to VSS	Examples
Agricultural land use spillovers 	Spillovers exist independently of VSS	• Intensive irrigation practices affecting surface or ground water levels (Haddeland *et al.* 2014; Velasco-Muñoz *et al.* 2019) • Wind- or waterborne erosion of (polluted) soils and their disposition elsewhere (Quinton *et al.* 2010; Smith *et al.* 2016) • Migrant workers applying their newly gained skills, knowledge and cultural habits elsewhere (Levitt & Lamba-Nieves 2011; Montefrio *et al.* 2014)
Supply chain spillovers 	Spillovers exist independently of VSS	• Purchase of farming inputs (e.g., fertilizers or pesticides) the production of which has adverse sustainability impacts (Barbieri *et al.* 2021; Li *et al.* 2023; Silva Pinto *et al.* 2020) • Processing and transport of farming products and related sustainability impacts (UNEP 2021) • Quality and safety of farming outputs affecting consumer health (Gomes *et al.* 2020; Reeves *et al.* 2019)
VSS adoption and implementation spillovers 	Spillovers as a consequence of VSS	• Non-certified farmers imitating sustainable practices of nearby certified farms (Läpple & Kelley 2015; Lewis *et al.* 2011) • Input reallocation due to additional profits gained through certification leading to land use changes elsewhere (Heilmayr *et al.* 2020; Ruben 2017) • Certification adoption affecting risk attitudes and investment behavior (Ruben 2017; Ruben & Fort 2012)

Table 1: Three types of spillovers in the context of agricultural VSS

Disentangling voluntary sustainability standard systems

The United Nations Forum on Sustainability Standards (UNFSS) defines VSS as "standards specifying requirements that producers, traders, manufacturers, retailers or service providers may be asked to meet, relating to a wide range of sustainability metrics, including respect for basic human rights, worker health and safety, the environmental impacts of production, community relations, land use planning and others" (UNFSS 2013, p. 4). Although such requirements are situated at the core of any VSS, they are not standalone tools but embedded in a larger system (Komives & Jackson 2014; Steering Committee 2012; Tscharntke *et al.* 2015). A standards system contains a "collective of organizations responsible for the activities involved in the implementation of a standard, including standard-setting, capacity building, assurance, labelling, and monitoring and evaluation" (ISEAL Alliance 2018, p. 30).

In this article, we disentangle VSS systems by characterizing five domains: VSS objectives and design; VSS setting; the standard document itself; VSS implementation; and engagement activities (Figure 2). Standard-setting organizations typically define a general vision and a set of core objectives and principles, which they then translate into more specific requirements and measurable indicators (Marx and Depoorter 2021; UNCTAD 2021). The design of the VSS system specifies elements that will achieve the VSS objectives (e.g., target group, scale and type of interventions). Standard-setting processes involve development and revision of standard documents. They are managed by the standard-setting organization, which can have varied governance structures in place (Bennett 2017). The standard documents contain the key requirements of the VSS and are implemented through different mechanisms. Compliance mechanisms verify that the VSS requirements are implemented by participating producers and businesses (e.g., through third-party audits). Traceability mechanisms track certified products from production site to point-of-sale. Labelling differentiates certified products from others for consumers and other businesses. Monitoring and evaluation (M&E) procedures inform compliance and learning within the VSS system. Finally, standard-setting organizations engage with certified producers and other stakeholders through engagement activities that support or complement the implementation of their standard. For example, they may provide capacity building and technical assistance to support farmers in their uptake of standard or community development programs (Tscharntke *et al.* 2015).

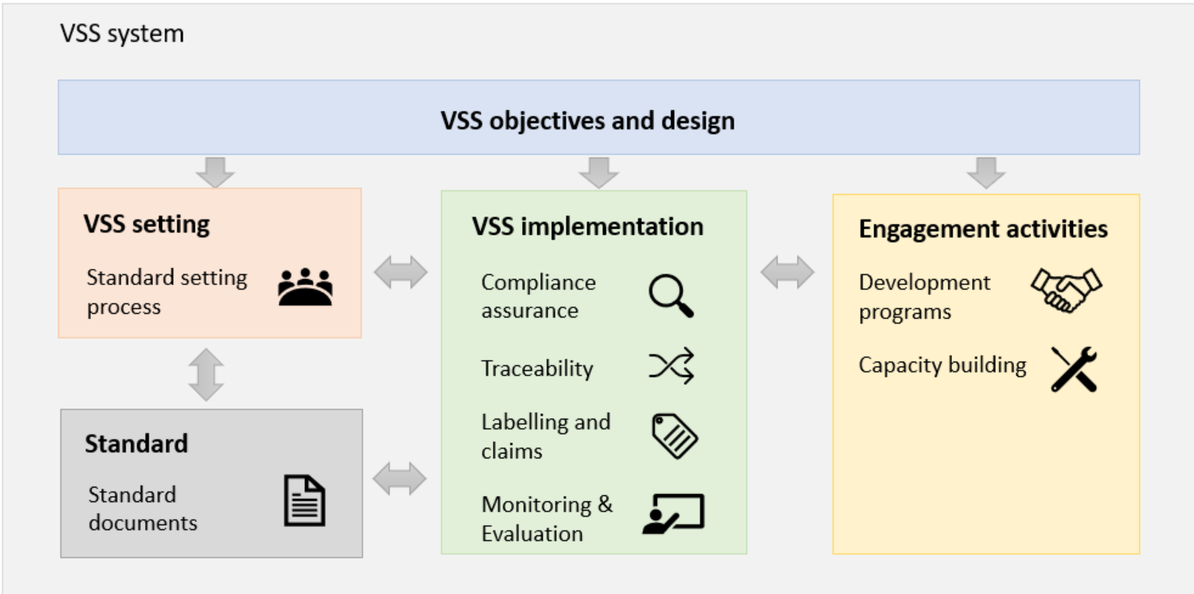

Figure 2: VSS system with five domains and their components. Source: Authors.

Entry points for integrating spillover perspectives in VSS systems

VSS systems are usually continuously evaluated and revised to address the ever-evolving sustainability challenges that they target (Arnold 2022; ISEAL Alliance 2014a, 2021). As dynamic and multifaceted governance instruments, they provide multiple potential entry points for taking up and integrating spillover perspectives. As indicated in Figure 3, different opportunities for this exist across the five domains of VSS systems introduced in Figure 2: 1) the objectives and design of VSS systems can set the overall direction and frame for governing spillovers; 2) standard-setting procedures can identify potentially relevant spillovers and deliberately set priorities in this regard; 3) the requirements stipulated in the VSS documents can regulate spillovers directly or indirectly; 4) different VSS implementation mechanisms can identify potentially relevant but not yet regulated spillovers; and 5) VSS engagement activities situated outside the direct certification realm (e.g., landscape initiatives) can identify and address potential spillovers.

In the following sections, we present selected entry points for each of the five domains of VSS systems (see Figure 3), provide illustrative evidence and examples regarding current practices, and link them to the good practice guidelines for VSS systems proposed by ISEAL Alliance, a global membership association that defines credible practice for sustainability systems (ISEAL Alliance 2022).

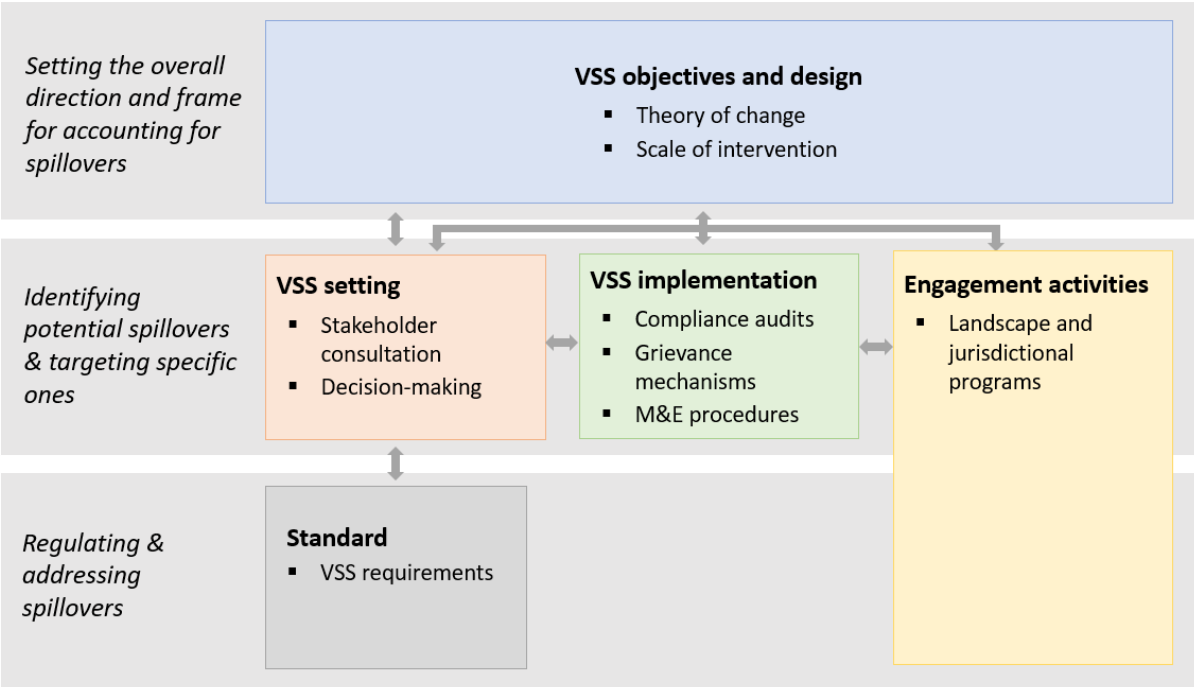

Figure 3: Selected entry points for integrating spillover perspectives into VSS systems. Source: Authors.

8. VSS objectives and design

The overall objectives and design of the VSS system set the precondition for the integration of spillover perspectives into VSS. Merely if sustainability challenges resulting from spillovers are prioritized and explicitly targeted at a strategic level, efforts will be undertaken to identify and address the respective spillovers at an operational level (e.g., in standard-setting procedures). Furthermore, the overall agenda drives the overall design features of the VSS system, which influence the potential of the VSS to address impacts beyond the farm level. In this section, we discuss two entry points for integrating spillover perspectives into VSS objectives and design: theory of change and scale of intervention.

1.1.1 Theory of change

VSS differ in what they aim to achieve. The recently published ISEAL credibility principles suggest that these systems should clearly define and transparently communicate their intended scope, sustainability objectives, and strategies for achieving these objectives (ISEAL Alliance 2021). A standard-setting organization thereby needs to define the thematic scope of their intended effects (e.g., what change do they strive to see? Who will benefit from it?) and their geographic scope (e.g., where do they want to see this change?). These strategic decisions considerably influence the extent to which the VSS can account for spillovers beyond the farm level.

Many standard-setting organizations develop a Theory of Change (ToC) to define and communicate the change they desire and the way they intend to contribute to it (Bray & Neilson 2017; Oberlack *et al.* 2023; Oya *et al.* 2018). A ToC describes the causal links between an intervention and its intended results, which are typically categorized as output, outcome, and impact (Belcher *et al.* 2020; Dhillon & Vaca 2018). The process of drafting or revising a ToC can offer a valuable starting point for explicitly discussing and defining priorities regarding the different types of spillovers relevant to the respective VSS system. Existing ToCs of VSS often present the aspired results through thematic scope, with limited indication of their geographic scope. One exception, the ToC of the Roundtable for Sustainable Palm Oil (RSPO), highlights limitations of interventions made within farm boundaries alone and defines healthy and resilient landscapes as one of their key goals (RSPO 2022). Furthermore, some standard organizations explicitly discuss their different scales of intervention (Rainforest Alliance 2021) or actor groups (Fair Trade USA 2021).

In addition to defining the scope of their intended effects, a ToC should also include strategies for dealing with *unintended* effects caused by VSS adoption and implementation spillovers (Dhillon & Vaca 2018; Oberlack *et al.* 2019). For example, certification activities can inadvertently affect local prices of agricultural inputs (Heilmayr *et al.* 2020) (see Table 1 for more examples). Unintended spillovers of VSS adoption and implementation are numerous and often difficult to detect, particularly if taking effect beyond the farm level (Bastos Lima *et al.* 2019; Heilmayr *et al.* 2020). Hence, it is important to distinguish whether they are knowable/unknowable and avoidable/unavoidable; Suckling *et al.* (2021) recommend focusing efforts on those that are knowable and avoidable. Strategies can be undertaken to foster learning processes regarding the unintended effects of standard systems (and thus increasing their knowability) through existing implementation mechanisms (see Section 5.4).

1.1.2 Scale of intervention

Agricultural VSS are usually designed to intervene primarily at the farm level, as they certify farmers (or groups of farmers) based on their actions within their farm. A straightforward way of adjusting VSS design to foster sustainability beyond the farm would thus be to expand or adjust the scale of intervention, e.g., to landscape or jurisdictional level (Lambin *et al.* 2018). Certification at landscape or jurisdictional level has been proposed by scholars as a potential more holistic way to address sustainability challenges (Deans *et al.* 2018; Glasbergen 2018; Tscharntke *et al.* 2015). In the case of palm oil production, initial efforts have been made to put this into practice. For example, the RSPO has piloted a jurisdictional approach to sustainable palm oil certification (RSPO 2021). It upscales RSPO's conventional approach to certifying mills and their supply bases through a group certification framework for whole jurisdictions. However, to date, standard-setting organizations have tended to engage in landscape programs (see Section 5.5) rather than broadening the scale of the certification intervention itself.

9. VSS setting

The standard-setting and revision procedures can serve to identify, discuss, and select spillovers to be targeted by the standard. By providing input, stakeholders can draw attention to potential needs regarding sustainability challenges beyond the farm level. Those who participate in and decide on standard-setting procedures are thus key aspects of an effective integration of spillover perspectives in VSS.

1.1.3 Stakeholder consultation

Good practice guidelines for standard-setting promote inclusive and transparent standard-setting processes that involve careful identification and recruitment of affected stakeholder groups[4] (ISEAL Alliance 2014a). The majority of agricultural VSS have stakeholder involvement procedures in place (Figure 4). Almost 70% (n=69) allow *any* interested stakeholders to provide input to the standard-setting process (e.g., through public comment periods). Furthermore, 79.7% present directly affected stakeholders with opportunities to participate in standard-setting (e.g., reaching out to them and actively encouraging their involvement). Most standard-setting organizations (68.1%) publish their uptake of stakeholder comments in the final version of the standard (see also Schleifer *et al.* (2019a) on transparency in standard-setting). Consultation of affected stakeholders can support the process

[4] Involving actor groups that are directly affected by the implementation of the standard or are interested in the application (ISEAL Alliance 2014a).

of identifying spillovers not yet included in a draft standard, particularly if explicit attention is paid to stakeholder groups affected by spillovers.

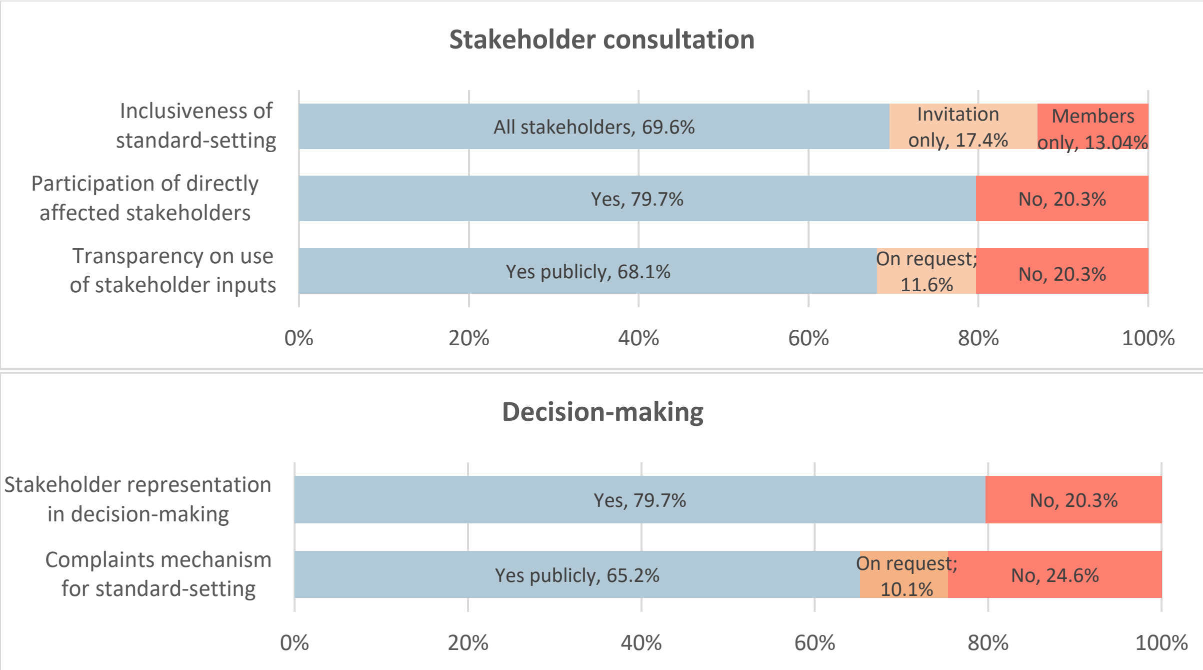

Figure 4: Illustrative evidence of VSS setting practices in agricultural standards (n=69). Source: Authors, based on data from the ITC Standards Map (2021).

1.1.4 Decision-making

Decision-making processes in standard development determine whether and which spillovers are addressed in standards. Good practice guidelines suggest that they should be informed, inclusive, and taken by governance bodies involving representatives of all stakeholder groups (ISEAL Alliance 2014a). Empirical evidence suggests that many VSS make efforts to include stakeholders in decisions on standard content. Analyzing 16 agricultural VSS initiatives, Potts *et al.* (2014) found that 69% involved external stakeholders (i.e., non-members) in decisions about VSS content. Our analysis further reveals that 79.7% (n=69) have voting procedures that ensure a balanced representation of all stakeholder categories (Figure 4). These procedures offer opportunities to support the assessment and potential prioritization of spillover-related sustainability challenges in standard-setting. However, there is an ongoing scholarly debate about the potential of stakeholder inputs to foster more stringent standards in standard-setting (Bennett 2017), which raises doubts about their actual potential to contribute to the integration of spillover perspectives into VSS (as further discussed in Section 6.2).

As spillovers often take effect outside of certification units (e.g., farms), VSS requirements targeting spillovers can be particularly challenging to implement and monitor. Hence, it is key to assess carefully which spillovers are/can be addressed through a standard. Feasibility studies can provide useful input for decisions on VSS contents, as they inform about the feasibility and auditability of proposed VSS requirements (ISEAL Alliance 2014a). To our knowledge, there is no empirical evidence for the overall use and quality of feasibility assessments or for their influence in decision-making procedures.

10.Standard document

Standard documents define requirements for sustainable practices of agricultural production (Komives & Jackson 2014). Situated at the heart of each standard system, the standards themselves constitute the most straightforward entry point to regulate spillovers through the specific requirements they put forward. VSS requirements can address spillovers either directly or indirectly, as outlined in the following sections.

1.1.5 Direct regulation through VSS requirements

VSS requirements can directly address spillovers by promoting or prohibiting practices that lead to processes with sustainability effects beyond the farm level. This applies to all three types of spillovers identified in Section 3. For agricultural land use spillovers, Sonderegger *et al.* (2022) present a detailed analysis of coverage of 21 such spillovers in the requirements of 100 agricultural standards, based on data from the ITC Standards Map. They find that spillovers are addressed in VSS requirements but to varied extents; environmental spillovers are more commonly regulated than socio-economic spillovers (Sonderegger *et al.* 2022). Our analysis of ITC data on the content of VSS further suggests that supply chain spillovers can also be directly addressed through VSS requirements. For example, VSS can include provisions requiring certified members to apply an environmentally friendly purchasing policy. Other examples include criteria for food quality and safety (e.g., requiring production practices that promote healthy or highly nutritional food). Figure 5 details the supply chain stages addressed in agricultural VSS. It shows that most agricultural standards regulate issues beyond the primary production stage, particularly those relating to production inputs and the processing of agricultural products. Issues beyond that are, however, less common. In addition, VSS requirements can address potential spillovers of VSS adoption and/or implementation. For example, if a standard prohibits child labor, it can require assistance to be given to (ex-)child workers and their families to cover their financial losses and prevent them from working again.

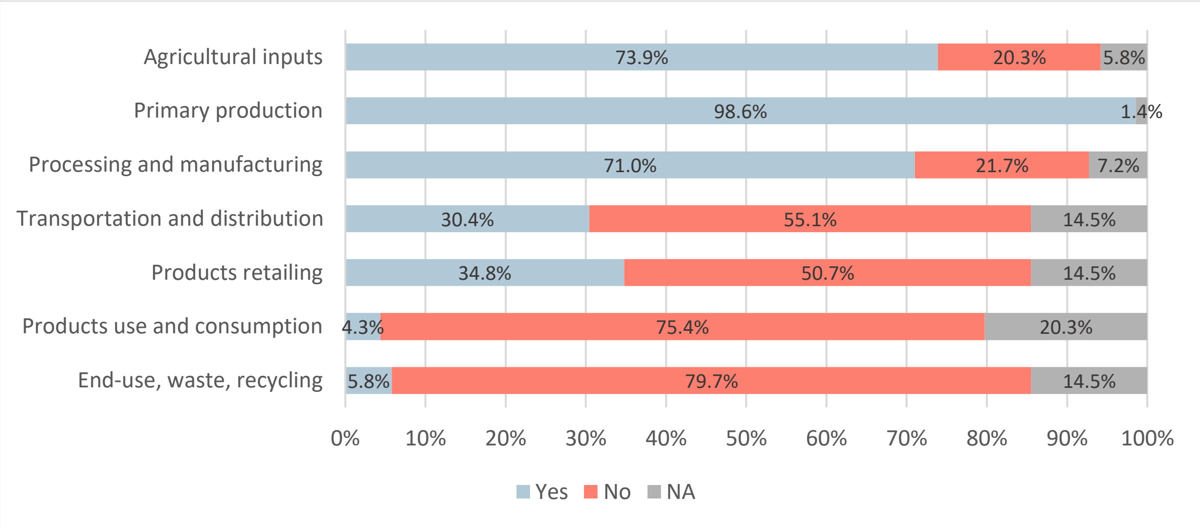

Figure 5: Supply chain stages addressed in agricultural VSS (n=69). Source: Authors, based on data from the ITC Standards Map (2021).

VSS requirements can target three different **components of spillover processes**, namely their triggers, the spillover processes themselves, and their impacts (Sonderegger *et al.* 2022). We illustrate this with an example of spillovers relating to resettlements caused by farmland acquisitions (World Bank & UNCTAD 2018). First, VSS can address triggers of such displacements, for example by requiring businesses to have valid user rights of tenure, defining the way land is acquired (e.g., through free, prior, and informed consent), and/or prohibiting such displacements altogether. Second, if not prohibiting them, they can regulate the spillover process itself, for instance by including requirements about the implementation of resettlement processes (e.g., requiring compensation and benefits for displaced persons or defining how the host communities are to be selected). Finally, VSS requirements can stipulate how adverse impacts on host communities have to be limited, for instance through effective livelihood development programs.

Figure 6 illustrates that, to date, VSS requirements most commonly target triggers for spillovers of agricultural land use. For example, in the case of spillovers of people displacement, 50% of relevant VSS requirement categories used in the ITC Standards Map target their trigger, 25% target the spillover process, and 25% its impacts. Figure 6 also shows that, for environmental spillovers, the spillover processes and impacts are more often targeted through VSS requirements compared to socio-economic spillovers.

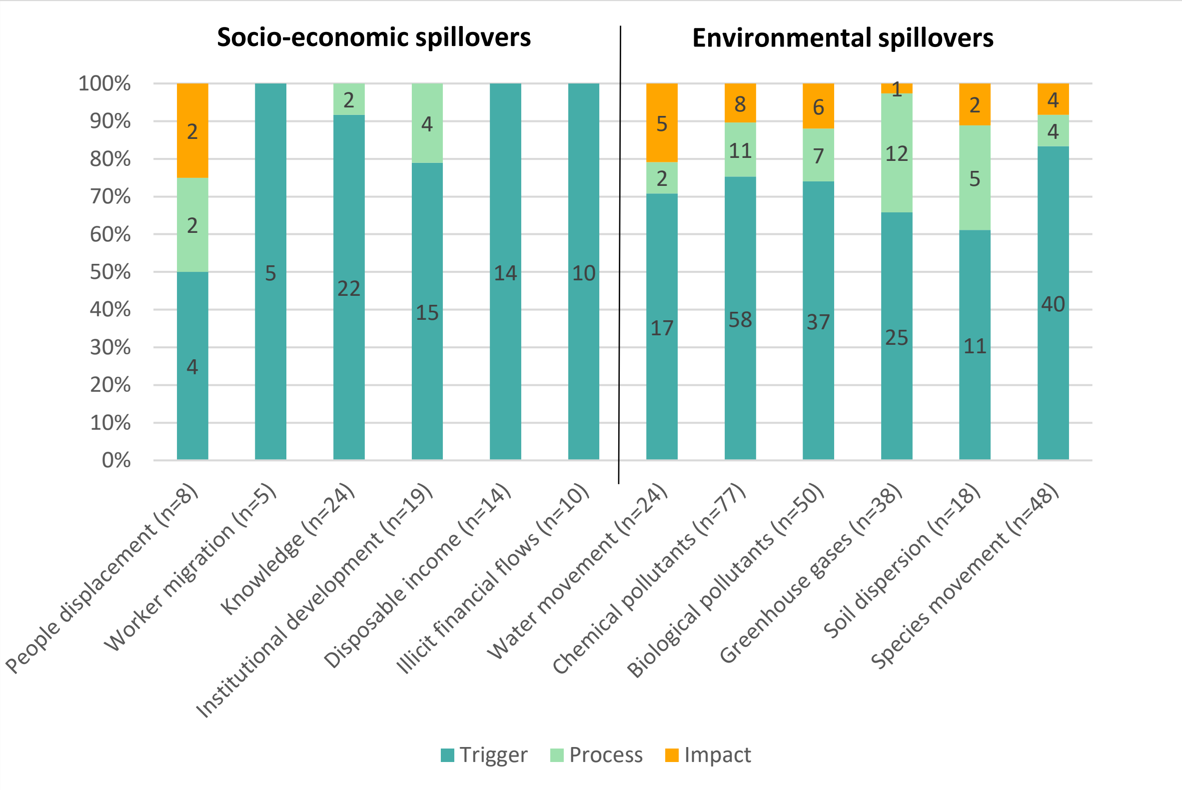

Figure 6: Relative share of spillover components addressed in VSS requirements for different spillovers of agricultural land use (see Sonderegger *et al.* (2022) for spillover definitions). Source: Authors, based on data from the ITC Standards (2021) and Sonderegger *et al.* (2022).

1.1.6 Indirect regulation through VSS requirements

VSS can also target spillovers more indirectly through requirements that call for the establishment and/or the implementation of governance instruments (e.g., impact and risk assessments, risk mitigation strategies, or management and action plans). These instruments can serve to identify and address spillovers in a context-specific manner. In practice, however, standard systems often lack the resources to assess whether and how these instruments are implemented (beyond assessing their mere existence). While this limits their potential to foster the consideration of spillovers through these instruments, they can nonetheless incentivize their members to do so.

11. VSS implementation

VSS implementation mechanisms can serve to identify potentially relevant but not yet regulated spillovers. This knowledge can be input into the standard-setting and revision process (see Section

5.2). Hereafter, we briefly describe selected tools and their potential role in identifying relevant gaps in existing standards.

1.1.7 Compliance audits

Compliance with the requirements set out in the VSS is generally verified through audit-based assurance systems (ISEAL Alliance 2018). A diverse set of assurance models exist in practice, ranging from first, second, and third-party assurance to combinations thereof (Blair *et al.* 2008; Loconto 2017). Audits are often expensive and burdensome and sometimes ineffective; thus, they are one of the main critiques raised regarding VSS (Bishop & Carlson 2022; LeBaron *et al.* 2017; Lebaron & Lister 2015; Schilling-Vacaflor *et al.* 2020). Solutions to these challenges are being sought. Existing auditing systems are being further developed and alternative verification systems designed and implemented; these rely on transparency, peer-review mechanisms, shared responsibility, and/or joint learning interactions between producers and their verifiers (Jacobi *et al.* 2023; Komives & Jackson 2014; Lamolle *et al.* 2019; Loconto & Hatanaka 2018). These ongoing developments can offer opportunities to integrate spillover perspectives into compliance verification processes. For example, audits typically involve interviews with producers based on a checklist of requirements stipulated in the respective standard. However, auditors may see and hear more than what this checklist contains. Hence, auditors could note down observations of potentially prevailing sustainability challenges beyond the farm, not yet included in the standard, and ask producers about any missing requirements; this could help to identify relevant spillovers.

Furthermore, the scope of audits could be expanded beyond the standard's direct scale of intervention. Currently, audits tend to cover smaller geographic units and do not often take place beyond the immediate farm. This is illustrated by data from the Standards Map. In our sample of 69 agricultural standards, 65% conduct audits at farm level, 48% at crop level, and 26% at field level, while only 6% apply audits within other legal boundaries (of the options presented, several may apply to a standard). Expanding audits beyond the farm level could involve conducting interviews with nearby communities in addition to the VSS adopters themselves. However, such an approach is likely to increase auditing costs and hence would require measures to prevent the producers from being further disadvantaged.

1.1.8 Grievance mechanisms

Disputes over the interpretation and application of a standard are inevitable (Potts *et al.* 2014). VSS systems should thus have accessible, fair, and effective grievance and dispute resolution mechanisms that enable stakeholders (e.g., VSS members, workers, and affected communities) to raise complaints about non-compliance with the standard's requirements and processes (Elder *et al.* 2021; Marx & Depoorter 2021; Twentyfifty 2022). Data from the ITC Standards Map indicates that the majority of agricultural VSS schemes have an internal complaints mechanism in place (75%). Although these non-judicial mechanisms are usually focused on compliance aspects, they could also be used to indicate unknown or insufficiently regulated spillover dynamics (e.g., by targeting them towards complaints about adverse impacts of VSS adoption or implementation).

In addition to the mechanisms established by standard-setting organizations, certified agricultural operations can also be required to have grievance mechanisms in place. If combined with a knowledge exchange with standard-setting organizations, these processes could highlight further spillovers (e.g., adverse sustainability impacts of agricultural practices not yet regulated through the VSS). Grievance mechanisms specifically set up for communities and other third-party stakeholders could therefore be particularly valuable (Shift *et al.* 2016). However, insights from VSS practice show this is less common: of the 69 agricultural VSS analyzed for this study, 20 (29%) require establishment of grievance mechanisms for affected communities, one recommends it (1%), and 39 (57%) do not cover it (data is lacking for nine VSS).

1.1.9 Monitoring and evaluation

Many VSS systems have Monitoring and Evaluation (M&E) mechanisms in place (see Figure 7). These serve to track progress towards intended outcomes and evaluate the long-term sustainability impacts of standards (as defined in their ToC; see Section 5.1.1). Performance measurement and standard improvement are therefore seen as their main purposes (Figure 7). To inform standard improvement regarding potentially unregulated spillovers, it is important not only to track the intended effects of the standard system but also to identify any significant and potentially damaging (also unintended) effects beyond the production unit (ISEAL Alliance 2014b; Schmitz-Hoffman et al. 2014). As data is collected for M&E purposes, specific methods can be applied to identify unintended effects (BetterEvaluation 2023).

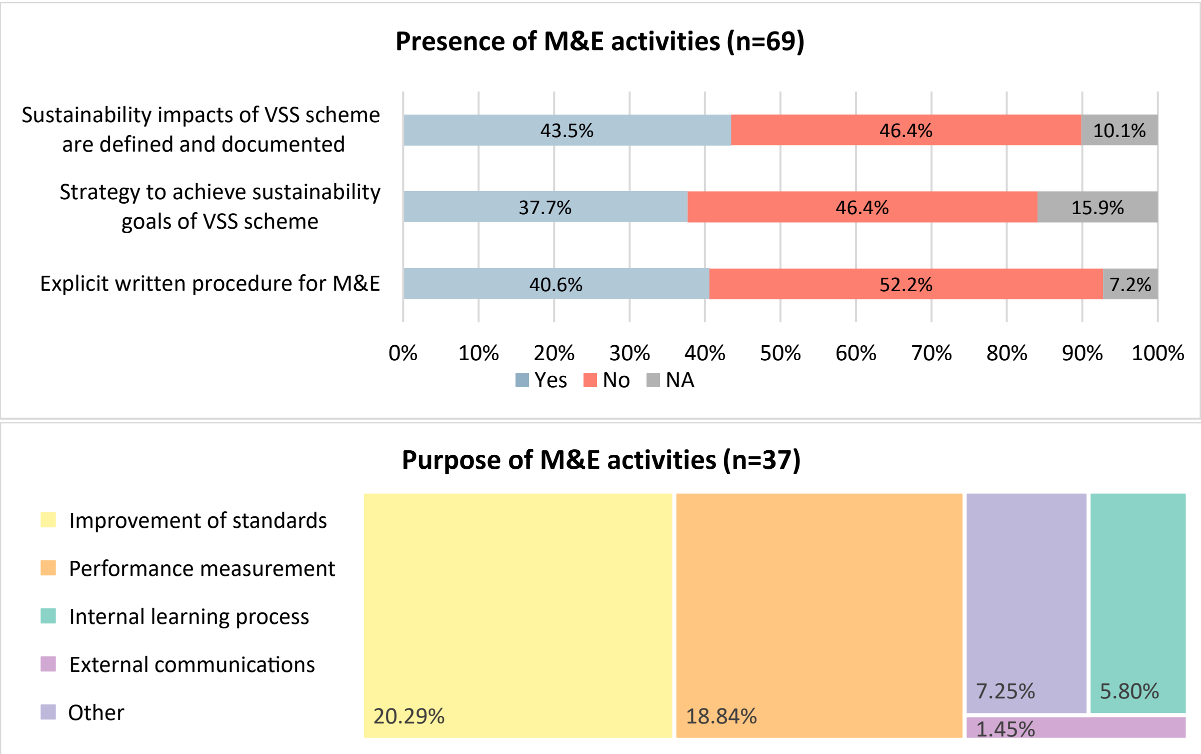

Figure 7: Illustrative evidence of M&E practices in agricultural standards. Source: Authors, based on data from the ITC Standards Map (2021).

12. Engagement activities

Engagement activities by standard-setting organizations (e.g., capacity building programs and community development projects) can offer entry points for standards to overcome limitations of certification by fostering positive impacts beyond the farm level. We hereafter focus on the example of landscape and jurisdictional programs.

For standards that primarily intervene at plot, farm, or supply chain level, certain spillovers are difficult to address (Sonderegger *et al.* 2022). Recent efforts by standard-setting organizations to achieve impacts beyond scale thus involve increasing engagement in non-certification activities that apply landscape or jurisdictional approaches (ISEAL Alliance 2017; Komives *et al.* 2018; Mallet *et al.* 2016). These are collaborative initiatives bringing together diverse stakeholders to reconcile social and environmental claims and objectives in establishing sustainable landscapes (Reed *et al.* 2020; Sayer *et al.* 2017). Jurisdictional approaches are a type of landscape approach with active government involvement, implemented within administrative boundaries (Denier *et al.* 2015).

The engagement of standard-setting organizations in landscape and jurisdictional initiatives is multifold. Rainforest Alliance, for instance, identifies landscape management as one of their core intervention activities besides certification (Rainforest Alliance 2022). Applying an integrated landscape approach, they develop and implement conservation and community development programs at landscape level (e.g., provision of training or facilitation of access to finances and market access) (Rainforest Alliance 2022). In October 2022, the Forest Stewardship Council decided to link the management of their certified units with collaborative landscape approaches (FSC 2022). Several standard-setting organizations are also engaging in the (co-)development of new tools to support landscape level assessment and monitoring activities (e.g., LandScale (Rainforest Alliance *et al.* 2020), Delta framework (Better Cotton 2022), and Landscape Monitoring Framework (FLOCERT & Fairtrade Max Havelaar 2022)). Taken together, these forms of wider stakeholder engagement in sustainability systems are likely to capture the interest of stakeholder groups who are positively or negatively affected by spillovers at landscape levels.

Barriers for integrating spillover perspectives in VSS systems

While each of the five domains of VSS systems offers entry points for integrating spillover perspectives in VSS, there are important barriers to their adoption and implementation, as discussed in this section.

13. Defining objectives: Are spillovers prioritized?

To make use of any of the above discussed entry points, spillovers need explicit attention and importance within a VSS system. This requires beyond-scale thinking when the objectives and designs of VSS systems are defined and further developed, as well as a prioritization of spillover-related challenges (see Section 5.1). Not every VSS needs to address spillovers; for example, spillovers may be beyond scope for highly specialized VSS.

Whether spillovers are considered and prioritized at a strategic level strongly depends on the interests of the respective decision-makers and the factors influencing their decisions. Such decisions are often taken by a higher-level governance body within the standard-setting organization (e.g., a board). They can be shaped by formal and informal communication with internal stakeholders (e.g., certified members). The prioritization of themes is also influenced by global sustainability discourses in academic and public debates, international agreements, private sector developments, and consumer preferences (Manning & Reinecke 2016; UNCTAD 2021). Moreover, standards do not function in isolation from each other; timely topics emerge within the VSS community (e.g., living income or deforestation). The resulting theme-centered priority setting can lead to a focus on selected spillover dynamics (e.g., GHG emissions), while others are given less attention. However, it does not allow for a more systematic, explicit consideration of different spillover dynamics and a prioritization thereof.

14. Setting the standard: (un)balanced stakeholder inputs and decision-making

Our illustrative evidence in Section 5.2 indicates that many agricultural VSS systems have provisions in place regarding the involvement of stakeholders in VSS-setting. However, does this automatically imply a significant potential to identify and take up spillover perspectives in the VSS setting? This question links to ongoing scientific debates about the quality of stakeholder inclusion and its effects on the stringency of standards (Marx *et al.* 2022; van der Ven 2022). Some scholars argue that standard-setting procedures are/can be democratic and that more inclusive decision-making procedures lead to better governance outputs (Beaulieu-Guay *et al.* 2021; Dingwerth 2007; Stevenson 2016). Others emphasize that with the inclusion of a diverse set of stakeholders, the standard-setting process is a constant process of negotiation (Brunsson *et al.* 2012; Manning & Reinecke 2016) and the search for overall consensus can lead to compromised solutions and less stringent standards (Bartley

2007; Newig *et al.* 2018; Ponte 2014). In such settings, unequal access to resources and power may hamper some stakeholders in defending their positions (Ponte & Cheyns 2013). Through a recent analysis of public comments on sustainability standards, van der Ven (2022) shows that stakeholder inputs are often unbalanced, with industry groups being over-represented. He finds "that comments intended to weaken the stringency of sustainability standards are more likely to be implemented than comments intended to strengthen their stringency" (van der Ven 2022, p. 1). Potts *et al.* (2014) point to a related dilemma of VSS: they strive for more sustainability, a concept that by definition considers the needs of all stakeholder groups. At the same time, standards have their specific target groups and are thus designed to respond to the needs of specific stakeholders (Potts *et al.* 2014).

These considerations call for a critical reflection on the potential barriers to stakeholder input in fostering the regulation of spillovers through standards. Addressing adverse spillovers through VSS requires more stringent standards with VSS requirements. However, these are not likely to be supported by the standards' main target groups, as they lead to increased cost and effort for internal stakeholders (e.g., producers), whereas external stakeholders (e.g., distantly located communities) benefit from their implementation. With the preferences of internal stakeholders potentially leaning towards less stringent requirements, settings with unbalanced decision-making are particularly challenging and the acceptance of more stringent standard requirements is difficult to achieve (van der Ven 2022). To gain approval, provisions regarding spillovers thus need to provide an incentive or added value for internal stakeholders (e.g., differentiation from other standards or consumer demands). In this context, it is also important to question whether it is fair or desirable to give equal voice in decisions about rule-making to all, including those who do not have to implement the standards' rules (Potts *et al.* 2014). This particularly applies in the case of less powerful actors with fewer resources (e.g., smallholders), who are often insufficiently involved in VSS governance and decision-making structures (Bennett 2017; Elder *et al.* 2021; Schleifer *et al.* 2019b). As they are likely to face constraints for implementing more stringent rules, targeted capacity building and other support mechanisms should be considered to address spillover dynamics through standards.

15. The standard: How to regulate spillovers?

Many existing VSS already implicitly target sustainability beyond farms through requirements in their standard documents, although this may be non-systematic (Kissinger *et al.* 2015; Sonderegger *et al.* 2022). While expanding this practice is a straightforward approach towards better regulation of spillovers through VSS, it also has risks. Expanding the coverage of a standard to account for a large range of spillovers leads to the introduction of more stringent and ambitious VSS requirements. This can negatively affect VSS uptake and exacerbate existing challenges in VSS implementation (Dietz & Grabs 2022; Haack & Rasche 2021; Sonderegger *et al.* 2022). This calls for a selective and adaptive approach to governing spillovers (Bastos Lima *et al.* 2019), combined with effective capacity-building efforts to support producers in their implementation of standards (Dietz & Grabs 2022; UNFSS 2020).

The findings in Section 5.3 showed that VSS often regulate the (on-farm) triggers of spillovers but less commonly target the spillover process itself or its respective impacts. VSS literature similarly distinguishes between different types of VSS requirements (i.e., performance- and process-based requirements; see Brunsson *et al.* 2012). Requirements in standard documents can either define the sustainability outcomes to be achieved or outline the practices to be undertaken without predetermining their specific outcomes (Potts *et al.* 2014). The majority of agricultural VSS define agricultural practices (Potts *et al.* 2014); few prescribe required outcomes (e.g., Buonsucro) or use hybrid versions (e.g., Rainforest Alliance) (Traldi 2021). Our results are thus in line with these observations.

This tendency to focus on-farm practices might be linked to the high levels of outcome variability and context-dependency in the agricultural sector (Potts *et al.* 2014). In the case of spillovers, these challenges might be further exacerbated, as spillover outcomes often evolve through complex, context-dependent causal mechanisms (Meyfroidt *et al.* 2020). In this context, outcome-based VSS requirements may provide for the necessary flexibility that allows producers to adopt the best-suited measures leading to a certain spillover outcome (Brunsson *et al.* 2012). However, assessing compliance with such standard requirements may be costly and challenging to implement, due to the potentially large geographic distance between the farm and the location where the spillovers take effect (Kissinger *et al.* 2015).

16. VSS implementation mechanisms: fit to inform about spillovers?

Audits, grievance mechanisms, and M&E procedures are three implementation mechanisms of VSS systems that can support the process of identifying unknown or insufficiently addressed spillovers (Section 5.4). Their potential to do so largely depends on whether the respective tools and processes are targeted towards spillover processes. The illustrative evidence of the ITC Standards Map highlights potential obstacles in this regard. The three mechanisms are usually not set up to account for spillovers: audits are commonly implemented at farm level, grievance mechanisms within VSS systems are typically compliance-focused, and M&E procedures have limited emphasis on the unintended effects of VSS. Furthermore, they have been criticized for design challenges and implementation failures (Harrison & Wielga 2023; LeBaron *et al.* 2017; Meemken *et al.* 2021; Milder *et al.* 2015; Wielga & Harrison 2021). Considering these challenges, existing implementation mechanisms may have limited capacity and readiness to aid in the identification of spillovers.

17. Engagement in landscape and jurisdictional programs: a way to address (some) spillovers?

Landscape and jurisdictional approaches have gained prominence in the quest to foster sustainable agricultural production "beyond the farm" and "beyond the chain" (Deans *et al.* 2018). VSS increasingly engage with such approaches, for example by developing certification at jurisdictional level (see Section 5.1.2) or, more commonly, engaging in landscape initiatives complementary to their certification activities (see Section 5.5). The interface between landscape/jurisdictional approaches and supply chain initiatives has gained momentum (Bastos Lima & Persson 2020; Boshoven *et al.* 2021; Kissinger *et al.* 2013; Ros-Tonen *et al.* 2018). Multi-stakeholder approaches at landscape/jurisdictional level are seen as promising instruments for addressing systemic sustainability risks on a more suitable scale than farm-level governance instruments (UNDP 2019; von Essen & Lambin 2021). This is particularly due to their potential to address negative externalities and spillovers occurring outside the scope of more common interventions at farm level (FAO 2017).

Despite these promising outlooks, landscape initiatives also come with considerable risks and potential implementation challenges (von Essen & Lambin 2021). Locked-in patronage systems, political turnovers, and power-laden and conflictual interactions between stakeholders can hamper the successful implementation of landscape initiatives (Delabre *et al.* 2021; Ng *et al.* 2022; Ros-Tonen *et al.* 2018; Schilling-Vacaflor *et al.* 2020). Furthermore, such initiatives can have leakage effects on other landscapes and jurisdictions (Boshoven *et al.* 2021; Delabre *et al.* 2021) and may neglect agricultural land use spillovers that go beyond the landscape level (Coenen *et al.* 2023). Hence, despite their comprehensive scope and broad scale relative to farm-level governance instruments, these initiatives are still limited to a certain geographic scale and thus unable to address spillovers that expand across a given landscape or jurisdiction.

Conclusions

VSS systems play an important role in fostering sustainability beyond scale and thereby accounting for the different types of spillovers that occur in the context of agricultural VSS. In this study, we identify concrete entry points and barriers for integrating spillover perspectives into VSS systems. They are situated within the different domains of VSS systems, ranging from the strategic decision-making level to standard-setting procedures, implementation mechanisms, and other engagement activities beyond certification. We find that VSS systems can make important contributions to fostering sustainability beyond farm level, through an explicit discourse about spillovers in strategic decision-making as well as targeted actions at operational levels. For instance, the process of defining the ToC of a VSS system can be used to reflect explicitly on where positive change is desired, who should benefit from it, and respectively, which (types of) spillovers should be targeted by certification and non-certification activities. Furthermore, existing VSS setting and implementation procedures (e.g., stakeholder consultations, feasibility studies, compliance audits, M&E procedures, or grievance mechanisms) can be designed and used to foster learning processes about (unregulated) sustainability risks that manifest beyond the production unit.

Each of the identified entry points faces barriers. It is thus crucial to reflect critically on the overall potential of VSS to address spillover-related sustainability risks. Based on our findings, two considerations arise in this regard. First, *standards are not suitable for addressing all types of spillovers equally well.* This requires continuous and systematic reflections on the existence, relevance, and governability of spillovers when a standard's scope, sustainability objectives, and VSS requirements are defined. In practice, however, strategic decisions and priority-setting in standard development are often discourse-driven and lack such a comprehensive assessment of spillover themes. Moreover, decisions about VSS contents are influenced by internal politics and affected by unbalanced stakeholder representations. This may not favor the integration of requirements on spillovers, due to the potential limited value added for the standards' certified members. Addressing these structural barriers in VSS systems is important, not only in terms of the integration of spillover perspectives into VSS, but also to ensure the credibility of VSS systems overall (ISEAL Alliance 2021).

Second, *spillovers cannot be addressed through standards alone*. As we have shown, VSS systems are increasingly expanding their portfolio through non-certification activities, such as initiatives at landscape level or interplay with hard law including due diligence regulations. These can serve to overcome some of the abovementioned limitations of VSS in fostering sustainability beyond the farm level. However, it is important to keep in mind that such initiatives are also confined to a certain geographic scale and thus face limitations in terms of addressing spillovers with sustainability effects beyond their landscape or jurisdiction. This example demonstrates that there is no one governance instrument that can alone address all spillovers. Consequently, while VSS have a role to play in this matter, their efforts need to link to those of other supply chain initiatives and governance instruments. It is thus key to foster transdisciplinary dialogues and learning experiences about the complementary role of different supply chain initiatives in fostering sustainability of agricultural production beyond the farm level.

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CRediT authorship contribution statement
Gabi Sonderegger: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. Andreas Heinimann: Writing – review & editing, Supervision. Christoph Oberlack: Writing – review & editing, Supervision.

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Supplementary material

18. List of Voluntary Sustainability Standards (VSS)

Table 1: Overview of VSS analysed in this study

Voluntary sustainability standard	**Latest update in Standards Map database** (during data collection)
4C – The Common Code for the Coffee Community	October 2020
Better Biomass (new name for the NTA 8080 Approved certificate)	November 2018
Bio Suisse Standards for Imports	November 2020
bioRe	July 2020
Bonsucro	September 2019
BOPP Standard Master (new name: Ornamental Horticulture Assurance Scheme (OHAS))	June 2019
CanadaGAP	Sep 2020
Cargill Triple S Soya Products	June 2019
China GAP	September 2018
Comercio Justo Internacional - Organizaciones de Pequenos Productores	December 2020
Cotton made in Africa	November 2019
Chinese National Organic Products Certification Program	June 2016
Donau Soja	March 2020
Equitable Food Initiative (EFI)	February 2019
EU Organic Farming	January 2020
Europe Soya	June 2019
Flowers and Ornamentals Sustainability Standard - Silver Level"	April 2018
Forest Stewardship Council® - FSC® - Chain of Custody	October 2020
Forest Stewardship Council® - FSC® - Forest Management	October 2020
Fairtrade International - Hired Labour	May 2020
Fairtrade International - Small Producers Organizations	July 2020
Fair Trade USA APS for Large Farms and Facilities	July 2017
Fair Trade USA APS for Small Farms and Facilities	January 2021
Baseline Code - Global Coffee Platform	November 2019
GLOBALG.A.P. Crops	June 2020
GLOBALG.A.P. Floriculture	April 2018
GLOBALG.A.P. Risk Assessment on Social Practice (GRASP)	September 2019
Hand in Hand (HIH) - Fair Trade Rapunzel	June 2019
IFOAM Standard	February 2018
ISCC EU	February 2020
ISCC PLUS	February 2020
KRAV	August 2019
Lineamientos basicos para un Cacao Sostenible - Organizaciones	March 2020
Lineamientos basicos para un Cacao Sostenible - Productores	March 2020
LEAF Marque	March 2020

McDonalds Supplier Workplace Accountability	June 2017
MPS-Socially Qualified (SQ)	April 2018
Naturland Fair	August 2020
Naturland Standards on Production	August 2020
OFDC Organic Certification Standard	March 2020
Protected Harvest Certification Standards: Stonefruit	March 2018
Protected Harvest Standards for Oranges and Mandarines	March 2018
Protected Harvest Standards for Lodi Winegrapes	March 2018
ProTerra Foundation	July 2020
Rainforest Alliance – 2020	February 2021
REDcert²	February 2019
REDcert-EU	February 2019
RSG Requirements (based on RTRS)	February 2016
Roundtable on Sustainable Palm Oil - Principles and Criteria	July 2020
Roundtable on Sustainable Palm Oil - Supply Chain Certification	May 2017
Red Tractor Fresh Produce Standards	March 2018
Red Tractor Combinable Crops and Sugar Beet Standards	March 2018
Reglamento Tecnlco para los Productos orqanlcos - Norma Peruana	November 2016
Round Table on Responsible Soy Association - RTRS	February 2018
Sustainable Agriculture Network - Rainforest Alliance - 2010	December 2015
Soil Association organic standards- farming and growing	April 2019
Sustainable Biomass Program (SBP)	December 2020
Sustainability Initiative of South Africa – SIZA	December 2019
Safe Quality Food Program	October 2020
Sustainably Grown	May 2020
Unilever Sustainable Agriculture Code	Jan 2019
USDA National Organic Program – NOP	May 2017
Vegaplan Standard for Primary Crop Production - Grains.	August 2019
Vegaplan Standard for Primary Crop Production - Potatoes.	August 2019
Vegaplan Standard for Primary Crop Production - Sugar beet.	August 2019
Vegaplan Standard for Primary Crop Prod. - Veg. for processing.	August 2019
Veriflora	June 2017
Wine and Agricultural Ethical Trading Association (WIETA)	May 2017
Zerya	May 2016