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Challenges and opportunities for operationalizing the safe and just operating space concept at regional scale

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Abstract

The concept of a safe and just operating space (SJOS) provided through combining the safe operating space (SOS) concept and the doughnut framework, delineates boundaries for ecological processes (e.g. climate change) and social wellbeing (e.g. food) at global scale. The integration of social wellbeing into the SOS concept through defining boundaries for humanity has become known as a SJOS concept. Although various studies have attempted to operationalize this SJOS concept, no synthesis has been conducted of the progress made and the obstacles faced. To address this need, we reviewed empirical studies and developed a conceptual framework of four operational steps for identifying the challenges and opportunities in operationalizing SJOS for regional social-ecological systems (SES). The steps include: 1) Understanding the SES to investigate the genesis in terms of selecting indicators and contextualization, which also include challenges such as selection of indicators, data availability and framework development to operationalize the SJOS concept; 2) Exploring the systems by understanding and unravelling the SES dynamics (e.g. feedbacks, nonlinearity) due to the limitation of existing modelling approaches; 3) Understanding the system governance by integrating stakeholders' visions and equity dimension of sustainability and conceptualizing the SJOS; 4) The communication of SJOS entails additional layers of complexity as this concept integrates diverse challenges (e.g. equity) and disciplines into the sustainability assessment. In contrast, overcoming the challenges offers opportunities for transformation to sustainability within the limits of SES across different scales. The operational framework can thus be used in assessing the sustainability of SES.

Keywords: *Planetary boundary, safe and just operating space, social-ecological systems, regional sustainability, transformation to sustainability*

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1. Introduction

Human development is increasingly pushing resource use boundaries to unprecedented limits beyond which the earth's biophysical processes are likely to become unsafe for human existence and biodiversity. These environmental limits, also known as planetary boundaries, capture critical upper thresholds of environmental change below which known biophysical processes are likely to continue to provide humanity a Safe Operating Space (SOS) (Rockström et al. 2009a, 2009b). Nine such biophysical processes have been identified (Rockström et al. 2009a, 2009b): climate change, ocean acidification, freshwater use, land-use change, biodiversity loss, nutrient cycles, ozone depletion, atmospheric aerosol loading, and chemical pollution. Among these nine earth system processes, three of them (climate change, biodiversity loss and nitrogen fixation) have already moved beyond the SOS. The Holocene (the last 11,000 years) has been used as the baseline to estimate the safe distance from thresholds for these nine earth system processes.

The SOS concept builds on earlier concepts to operationalize sustainable development such as limits to growth (Meadows et al., 1972), safe minimum standards (Ciriacy-Wantrup 1952, Bishop 1978, Crowards 1998), the precautionary principle (Raffensperger and Tickner 1999), carrying capacity (Daily and Ehrlich 1992) and the guardrails concept developed by the German Advisory Council on Global Change (WBGU 1998; 2006). In particular, Guardrails refer to thresholds of global change that "cannot be crossed without incurring excessive damage to humanity and the environment", and when a global risk (e.g. the risks of climate change, biodiversity loss, soil degradation and food insecurity) falls within "...a boundary zone - a critical zone", "particular care and special precautions need to be taken" and need to "keep the risk within boundaries accepted by society (WBGU 1998: 4). The SOS concept also extends the ecological footprint concept used to describe human impact on the biological capacity of the earth (Rees 1992; Wackernagel 1994) by integrating the idea of critical limits. Thus, the SOS concept quantifies the global ambition of acceptable and unacceptable risks and provides the opportunity to manage human development within the safe space in response to increasing anthropogenic pressure on planetary boundaries (Carpenter et al. 2016; Willcock et al., 2016; Lewis 2012).

The SOS framework has significantly influenced international discourses on sustainability in both academia and policy and has been used in defining the UN Sustainable Development Goals (SDGs) (Cole et al. 2014). It has been applied at national (e.g. the "Green Economy" action plan of Switzerland, the Swedish Environmental Protection Agency, and the Netherlands Environmental Assessment Agency) and at international levels (e.g. the United

Nations' high-level panel on global sustainability (2012), the European Union 7th Environmental Action Program). Furthermore, private sector actors (e.g. Swedbank) and civil societies (e.g. WWF, Oxfam) (Keppner et al. 2017; Nordhaus 2012; Lewis 2012) have embraced the concept.

Besides attaining policy and academic attention, the SOS concept has also faced criticism for not including the social system or interactions among variables, and in terms of the normative settings of the boundary and scale (Hossain et al. 2016; Lewis 2012). Raworth (2012) thus extended the concept to integrate the social system, including and defining thresholds for eleven social domains (e.g., food, income, education, health) below which human deprivation is unacceptable. The resulting approach (the doughnut concept; Raworth 2012) defines "a safe and just operating space for humanity" (SJOS), highlighting the critical links in socioeconomic development between human needs, poverty eradication and environmental sustainability. The extension of "safe" and "just" as normative criteria has raised attention both in research and public policy as well as in global development, and holds the potential for an integrated analysis of the complex interlinkages between environmental, social and economic dimensions of sustainability.

Subsequent work has focussed on improving the assessment of individual boundaries (e.g. Mace et al. 2014; Carpenter and Bennett 2011), on operationalizing the concept at national (e.g. Dao et al. 2018; Cole et al. 2014; Nykvist et al. 2013) and sub-national (e.g. Hossain et al. 2017; Dearing et al. 2014) levels. While various countries and studies have attempted to apply the SJOS as a tool for assessing progress towards sustainability, no synthesis has been conducted of the progress made and the obstacles faced while operationalizing the SJOS at regional scale. Previous studies (Downing et al. 2019 and Häyhä et al. 2016) have mainly focused on the SOS concept at the global and national scale and missing perspectives (e.g. social dimension, resilience) from the original PB concept. Häyhä et al. 2016 identified three dimensions (complex relationships of biophysical, socio-economic, ethical) and plausible approaches and tools for bridging the gaps between global and national scales. However, no study has focused on identifying the challenges and opportunities for operationalising the SJOS at a regional scale.

We thus review papers and develop a conceptual framework to identify the challenges to and opportunities for further operationalising the SJOS at regional scale, drawing on past studies and applications. We limited our focus on the conceptual and methodological challenges to meaningfully translate SJOS and provide practical implications for overcoming the challenges at regional scale. Although, the methodological approaches to overcome these

challenges is beyond the scope of this paper, identifying these challenges may increase the acceptability of the SJOS in the decision-making process. In addition, the conceptual framework developed in this paper, can be used for understanding and assessing the sustainability of social-ecological systems across different scales.

2. Methodology

2.1. Defining regional scale

In order to make the SJOS concept work for assessing global sustainability, we need to account for regional differences and problems, mainly because 1) many of the earth system processes (e.g. land use, fresh water) are mostly governed and aggregated from regional scale problems, and 2) while policies, laws and regulations may be developed on a national scale, they are subject to different regional scale interpretations and applications.

In general, a regional scale can range between 10^4 to 10^7 km^2, which could be referred from local to sub-continental scale (IPCC 2001). However, the definition of regional scale is complicated in terms of operationalization, as defining the its boundary can be based on socio-political (e.g. administrative), ecological (e.g. agro-ecology, climate homogeneity) or geographical (e.g. sub-continental) considerations. Therefore, the definition of regional scale depends on the purpose and question of the study (O'Neill et al. 1996). In this study, we argue that the SJOS needs to operationalize at a scale, at which decisions are made and actors have the legitimacy to implement the decisions (Cash et al. 2006). Thus, we refer regional scale as the sub-national level, which can vary from watershed to river basin, or it may include sub-national administrative divisions, wetlands, coastal or agro-ecological zones depending on the context of the sustainability assessment (Dearing et al. 2014)

2.2. Review strategy

This review focused on the empirical studies (SI Table 1) on planetary boundaries, safe operating space, safe and just operating space, drawing on scientific journal articles, project and workshop reports written in English language. We limited our review to empirical studies (Total 17 papers; see SI Table 1) which aimed at operationalizing the three concepts (PB, SOS and SJOS) or at least developed (e.g. Häyhä et al. 2016) a conceptual framework to support their operationalization across different scales (global, national and regional). For this reason, our review did not include any review or perspective papers, which did not operationalize these concepts with empirical examples. However, we draw on such review or perspective papers to strengthen our arguments on the operationalization of the SJOS concept at regional

scale. We may thus have missed some empirical studies in our review, but we expect that our approach offers us adequate material to identify key challenges to and opportunities for further operationalizing the concept. SI Table 1 provides the overview of the scale, approaches, limitations and challenges in the reviewed key papers which operationalized the SOS and SJOS concepts. In addition to the reviewed key papers on the operationalization of these (PB, SOS and SJOS) concepts, we also reviewed studies, which discuss the challenges such as understanding and unravelling of SES, incorporating justice and equity in order to complement the findings of this review.

2.3. Conceptual framework

We develop a conceptual framework (Fig 1) to identify and overcoming challenges by adopting a transdisciplinary approach (Pohl and Hadorn 2007), that integrates interdisciplinary scientific perspectives with those of other societal actors to generate three types of knowledge: systems knowledge (empirical knowledge), target knowledge (what needs to be changed), and transformation knowledge (how to induce change). Based on the review papers, we extended the three types of knowledge production (Pohl and Hadorn 2007) by conceptualizing four operational steps for identifying the challenges in operationalizing SJOS for regional SES: 1) understanding the SES to investigate the genesis (e.g. selecting indicators and scale), contextualization and formulation of the problems, which bring challenges such as indicators selection, conceptualization and data availability; 2) exploring the system in order to understand and unravel the interlinkages and feedbacks and how the SES works – system exploration not only provides the system knowledge but also helps identify the demand for change, plausible transformative pathways and practices based on the understanding (historical and current) of SES; 3) understanding that system governance integrates the stakeholders' visions in determining what needs to be changed for transformation to sustainability – possibly, this also provides the transformative knowledge (how to induce change) by integrating perspectives and visions of diverse key decision-makers into defining the SJOS and normative judgments about how societies choose to deal with risk and uncertainty. However, the transformation knowledge (how to induce change) is beyond the scope of this paper; 4) communication, which requires understanding how to convey a clear and meaningful translation of the science and the practical implications of SJOS concepts to policy-makers.

3. Challenges

SI Table 2 provides lists of the conceptual and methodological challenges and opportunities in operationalizing the SJOS concept at regional scale. Considering the structure of conceptual framework (Figure 1), section 3.1 introduces the challenges in understanding systems (e.g. selection of indicators, challenges of data availability, scale and framework), before discussing the challenges (e.g. unravelling SES dynamics, limitations, uncertainty) of system exploration (Section 3.2) in understanding SES dynamics. Section 3.3 introduces the challenges (e.g. conceptualizing and defining the SJOS, incorporation of justice equity and actor's visions) in system governance, before presenting the (Section 3.4) the challenges of visualization and communication while operationalizing the SJOS concept at regional scale.

3.1. Systems understanding

System understanding refers to the ability to recognize or be familiar with a SES's characteristics and nature in order to acquire the knowledge for an adequate representation that enables problem-solving (Arnold and Wade 2015; Hieronymi 2013). This systems understanding involves the investigation of genesis, contextualization and formulation of the problem, identifying indicators, scale selection, conceptualization, and data availability. The overall discussion to explore challenges of system understanding for operationalizing the SJOS concept comprises six key points: 1) a critique of the use of Holocene for initial indicators selection; 2) negligence of social dimension in the SOS concept; 3) contextualizing the indicators; 4) developing a framework; 5) selecting appropriate scale (e.g. temporal, ecological, economic) and; 6) data availability for operationalizing SJOS. These six challenges are discussed in greater detail below.

3.1.1. Selection of indicators

In sustainability science, indicator has been referred to as a communication tool (Moldan and Dahl 2007), which simplifies complex reality (Galli et al. 2012) and allows the measurement of performance (Moran et al., 2008) of economic, social and environmental processes in order to achieve the sustainability of SES. Indicators enable to infer the conditions of phenomena under study. Such conditions can vary over time, space and in the degree of their manifestation. While assessing the sustainability of SES using the SJOS concept at regional scale, it is important to ensure that selected indicators depict the complex SES in a realistic way, that it captures the economic, social and environmental processes, and considers environmental and actors' priorities in that respective scale. In general, the selection of indicators for operationalizing SJOS is particularly challenging in terms of initial indicators (Section 3.1.1.1),

negligence of social dimension and other social foundations (Section 3.1.1.2) in SOS and SJOS concepts, contextualizing the indicators (Section 3.1.1.3) and types and spatial context of indicators (Section 3.1.1.4).

3.1.1.1. Holocene as a baseline and debate about the initial indicators

Rockström et al., (2009a) used Holocene as the baseline to define the boundaries; however, many of the indicators other than climate do not represent a suitable environment for human development in Holocene. The use of species richness as one of the indicators for planetary processes has been debated in terms of abundance, community composition and ecosystem level interaction (Mace et al. 2014). Similarly, the land use change indicator has been criticized, as it does not specify which types of land would be more or less harmful to convert for agriculture practices (Nykvist et al. 2013).

SI Table 3 provides an overview of how the indicators of the original planetary boundary approach (Rockström et al., 2009a) are operationalized in the reviewed key papers. Studies such as O'Neill et al. 2018, Dao et al. 2018 and Nykvist et al. 2013 downscale the planetary boundaries to national scale following the initial indicators used by Rockström et al. (2009a). However, many of the indicators such as ocean acidification, ozone layer depletion, and biodiversity were excluded from their list of boundaries, considering contextual aspects of the case studies. Similarly, Cole et al. 2014 adopted marine harvesting, eutrophication and air pollution indicators while downscaling the boundaries such as ocean acidification, chemical pollution to national scale. In contrast to the national scale studies, the regional scale studies (e.g. Cooper and Dearing 2018, Hossain et al. 2017) operationalized the SJOS concept using different indicators (e.g. water quality regulation, shrimp production, fishing) in the context of regional sustainability. It thus remains challenging to apply a similar set of indicators across scales.

3.1.1.2. Initial neglect of social dimension and other social foundations

In contrast to the biophysical system, the social indicators are paid less attention while operationalizing SJOS (SI Table 4). Though the gender equality dimension (the employment and representation in parliament gap between men and women) was included by Raworth (2012), the educational and health issues of women were excluded (e.g. Cooper and Dearing 2018, Hossain et al. 2017; Cole et al. 2014) when selecting indicators for the SJOS concept. Later studies have paid less attention and often excluded gender equity as a social foundation when selecting indicators to operationalize the SJOS concept across different scales.

After introducing the social foundations laid by Raworth in 2012, Cole et al. 2014; Dearing et al. (2014) and Hossain et al. (2017) included social dimensions while operationalizing the SJOS at national and sub-national scales. However, both Cole et al. (2014) and Dearing et al. 2014 revised and added other social indicators based on the context of their case studies. For example, Cole et al. 2014 separated the dimension of water used by Raworth (2012) into sanitation and water. They also argued that the resilience indicator proposed by Raworth (2012) is the cumulative effect of all other social and ecological dimensions. In contrast to Cole et al. (2014) and Raworth (2012), Hossain et al. (2017) only used income, GDP and production cost as the key indicators to define the SJOS considering the for the complex dynamics between social (e.g. GDP, income, subsidy) and ecological (e.g. climate, water, salinity) systems. They argued that considering the social-ecological settings of the region, the society may transgress the SJOS, if all these three indicators decline substantially below a certain threshold. Hence, the importance of different social foundations across case studies vary..

3.1.1.3. Contextualizing the indicators

All of these (3.1.1.1 to 3.1.1.2) hint that despite some advances, the operationalization of the SJOS concept at regional scale faces challenges in selecting indicators appropriate to the context and purpose of the study as well as in maintaining compliance with global and national policies and social norms. Furthermore, it may also be important to maintain coherence with the original PB and SJOS concepts, not only in terms of downscaling the SJOS concept to regional scale, but also in terms of linking the regional SJOS with national and global SJOS. Considering these challenges, we identify the following three key tasks in selecting indicators to operationalize SJOS at regional scale:

I. What are the indicators that represent SJOS for humanity at regional scale?
II. What are the indicators that translate global planetary boundaries to regional scale? Are there any global indicators for local conditions and processes?
III. What are the indicators that link sub-national, national and global SJOS?

3.1.1.4. Types and spatial context of indicators

Besides all these, several other challenges could arise. First is the question of single-issue or multiple-issue indicators; it has to be decided whether to use a single-issue approach for selecting indicators (e.g. net primary plant production (Running 2012) and phosphorus (Carpenter and Bennett 2011)) or multiple-issue indicators such as comprehensive sets of indicators (e.g. Rockström et al. 2009) while downscaling the SJOS to regional scale.

Furthermore, the selection of an index-based approach (e.g. Human Development Index or Air Quality Index) could transform into composite indicators aggregated from several single indicators (Brink 2006). In contrast, divisions of indicator (e.g. poverty) into sub-indicators (e.g. per capita income, GINI coefficients) can be considered to account for the complexity and limitations of using single indicators.

Secondly, the selection of indicators raises another challenge of identifying the slow and fast variables within the list of selected indicators. Slow variables (e.g. climate) act as controlling and shaping variables for fast variables (e.g. food provision) and ecosystem resilience (Mace et al. 2014; Biggs et al. 2012).

Thirdly, the spatial context of indicators can add an extra layer of complexity to the selection of indicators challenge, as the same indicator may have different meanings when applied in different contexts (Moldan and Dhal 2007). For example, shrimp farming could be an important indicator for environmental degradation (planetary boundary) in mangrove or agriculture-based regions, whereas the same indicator can be considered a source of livelihood (social foundation) and may not capture the degradation of the environment in a highly saline region. This example highlights the challenges that shrimp farming can be an indicator for both planetary boundary and social foundation.

3.1.2. Lack of framework for operationalizing SJOS concept

Besides all these challenges in conceptualizing and defining SJOS at regional scale, the lack of a standard framework for operationalizing SJOS at regional scale adds another layer of complexity in using the SJOS concept for comparing progress towards sustainable development. Dearing et al. (2014) proposed a new framework using system properties to operationalize the SJOS concept at regional scale; however, it does not provide guidelines on how to deal with the dynamics within and between social and ecological systems or how to integrate the idea of justice and equity. Häyhä et al. (2016) highlighted the DPSIR (Driver-Pressure-State-Impact-Response) as a plausible framework to downscale SJOS at national scale, but this framework also has shortcomings in terms of accounting for changes in social-ecological dynamics, clarity of cause-effect relations (Gari et al. 2015; Rekolainen et al. 2003) and oversimplification of real-world complex environmental problems (Ness et al. 2010). Therefore, development of a framework is required not only to integrate the social, economic and ecological dimensions and the changing dynamics within and between all three dimensions, but also to integrate the equity and justice dimensions in order to operationalize the SJOS concept at regional scale.

3.1.3. Selecting appropriate scale

Resolving scale issues is a classical challenge in social-ecological studies (Cash et al., 2006). The PB and SJOS concepts emphasized global-scale ecological processes and social deprivation. However, many of the ecological processes are aggregated from regional scale (Lewis 2012) and the political and economic trade-offs of human wellbeing take place at the local and regional scale (Nordhaus et al. 2012). Therefore, specifying SJOS at global scale may misguide local and regional policies (Hossain et al. 2017) and make it hard to present SJOS concepts to policymakers. In this context, to make the SJOS concept work and influence policies, translation of this concept at an appropriate scale is required (Keppner et al. 2017). This raises key challenges in selecting the appropriate scale, even within the regional scale, in terms of spatial and temporal scales of phenomena or observations.

3.1.3.1. Economic vs ecological scale

The debate over economic and ecological scale is crucial, as the ecological and economic boundaries seldom coincide (de Groot et al. 2010; Cash and Moser 1998). For example, ecological zones such as the high yield potential zone of Kenya or the Ganges flood plain in Bangladesh often mismatch with the economic boundaries, which are often recognized as jurisdictional or political boundaries. As policies are implemented on the basis of economic boundaries, remapping of ecological boundaries into economic boundaries is usually required (Moldan and Dahl 2007) or negotiated across jurisdictions. Even within the economic boundaries, selection of small scale (lowest level of jurisdictional boundary) over large scale (highest level of jurisdictional boundary) is often dependent on the purpose of the study. Dealing with small scale is less complicated, though it can be enriched by diverse relationships and conflicts at local scale. In contrast, large scale is highly complicated and often involves oversimplification of relationships in order to conceptualize and understand SES (Wilbanks 2007).

Although the economic scale is often emphasized due to the policy relevance, the ecological scale is also crucial both for political and sustainability aspects. For example, the operationalization of SJOS for deltas (e.g. Niger Delta, Mekong Delta) or transboundary water management in South Asian countries can be more policy-relevant and can contribute to managing SES and resolving conflicts in a specific context.

3.1.3.2. Selecting appropriate temporal scale

A key challenge for operationalizing the SJOS at regional scale is to select an appropriate temporal scale in terms of trade-offs between short-term and long-term scale and a reflection of temporal dynamics (e.g. time lag). The temporal scale of SJOS has received less attention, as most international discourses mainly debate the appropriate spatial scale for operationalizing the SJOS. It is essential to understand the temporal dynamics of both ecological and social systems to develop strategies for the transition to sustainability. The short-term perspective may be more relevant for policy, as decisions are made mainly with respect to political considerations, promises and regimes. For example, from a political perspective, the inter-annual temporal aspect of SJOS may be more meaningful with respect to the transboundary water dispute in Asia (Szabo et al. 2018). Furthermore, the way a country performs within the SJOS under a specific political regime (e.g. five-year plan) can be more meaningful for its policy makers. In contrast, the long-term (e.g. achieving SDGs by 2030) perspective is also important for understanding the co-evolution and changing dynamics of the SES and the extent to which the social system can afford changes in the ecological system (Birkhofer et al. 2015; Biggs et al. 2012). The lag times between cause and effect can also be critical depending on the temporal scale and purpose of the study (Moldan and Dahl 2007).

The original PB considered Holocene as the baseline, which has been debated, as many of the ecological processes during the Holocene were not suitable for human development. For example, returning to the Holocene state of land use or freshwater may not be beneficial for human wellbeing. To approximate current SJOS, Cole et al. (2014) and Dearing et al. (2014) analysed historical time series data. Recent advancements (e.g. Cooper and Dearing 2018; Hossain et al. 2017) used 50 years of model run to investigate what drives the system out of SJOS; however, many of the ecological processes (e.g. sea level rise) may take longer than anticipated (IPCC 2007) and could mislead policies by excluding the plausible impacts of these ecological changes. Both short term and long-term approaches can be useful for incorporating the current and historical distant impacts of local consumption. Therefore, a key challenge is to decide the appropriate spatial and temporal scale for operationalizing SJOS in a transdisciplinary manner that integrates multiple perspectives and values.

3.1.4. Data availability

Data availability is tightly connected with the selection of indicators, as the selection of indicators is often constrained by the availability of relevant and quality data. A paucity of high quality data is one of the major challenges in ecosystem services assessment (Birkhofer et al., 2015). This could possibly be a reason for the lack of systematic quantification of system

resilience and understanding of how long social systems can afford changes in ecological systems (Raworth 2012). Even national scale studies on social-ecological processes such as those focusing on land use (Kuemmerle et al. 2013; Verburg et al. 2011), biodiversity (Mace and Baillie 2007), deforestation (Hosonuma et al. 2012) or water quality (Haung and Xia 2000) are constrained by data availability, and selecting these indicators at regional scale and beyond could be highly challenging due to data unavailability. For example, the indicator from original PB boundaries such as biogeochemical flow (e.g. amount of nitrogen removed from atmosphere for human use) could be challenged in order to operationalize at regional scale and analyse the regional contribution to global boundaries due to the quality database of nitrogen loading at the regional scale (Reis et al. 2016).

Similar to ecological indicators, social indicators often lack time series data and a uniform definition, which, ultimately, poses a challenge even to analysis and comparison at national scale (Chen et al. 2013). The databases did not improve much within the Millennium Development Goals (MDGs) programme (Sarvajayakesavalu 2015; SDSN 2014), despite commendable progress made in achieving MDGs across the globe (Hossain et al. 2015). In such a case, some of the indicators of the SJOS concept (Raworth 2012) such as networks, peace and justice and political voice may have to be excluded due to lack of sufficient data even at national scale. Thus, similar to other sustainability science concepts, the SJOS concept is challenged by data unavailability, which becomes worse in developing countries (Ndzabandzaba 2015) and when moving beyond the national scale.

3.2. Systems exploration

Systems exploration aims at understanding and unravelling the interlinkages and feedbacks and exploring how a SES works. This also helps identifying the demand for change, plausible transformative pathways and practices based on the understanding (historical and current) of the SES. The overall discussion to explore the challenges of system exploration to operationalize the SJOS concept, is focused on the understanding and unravelling social-ecological (SES) dynamics, which highlights the challenges of incorporating SES dynamics into SJOS concept, limitation of existing modelling approaches and uncertainty of defining SJOS considering SES dynamics. The challenges of system exploration to operationalize the SJOS concept at a regional scale, are discussed in greater detail below.

3.2.1. Understanding and unravelling social-ecological dynamics

3.2.1.1. Incorporating SES dynamics into SJOS concept

The original PB concept (Rockström et al. 2009a) and the SJOS concept (Raworth 2012) have been criticized for excluding the interactions among the biophysical boundaries and the complex dynamics of SES systems (Hossain et al. 2017; Cole 2014). SES dynamics typically arise from the interactions and feedbacks between the variables (Hossain and Szabo 2017). Within the original PB approach, climate change and land use are among the nine planetary processes, which interact, such as, land degradation influences climate, which in turn, influences the land use pattern across different scales. At regional scale, the coastal shrimp farming offers a good example for understanding the SES dynamics. For example, shrimp farming reduces mangrove biodiversity, which increases salinity, which in turn, improves conditions for and increases shrimp farming, which causes further reduction of mangrove biodiversity. Self-perpetuating feedback loops and interactions in SES often lead to nonlinear changes or regimes shift if certain thresholds are crossed. For example, maize production declines drastically when a certain temperature is crossed and when rainfall declines during certain periods of maize growth (Schauberger et al. 2017). In addition to the interactions and feedbacks in SES, there is often delay (time lag) between the time of crossing the threshold temperature and the decline in maize production. This phenomenon known as time lag effect adds additional complexity to SES dynamics.

3.2.1.2. Complexities and limitations in modelling SES

Understanding and unravelling such types of SES dynamics are one of the major challenges to operationalize the SJOS concept for the regional SES. Though the notion of SES dynamics is increasingly used in academia (Leenhardt et al. 2015), feedbacks in SES are poorly understood and often conceptualized (Verburg et al. 2015), rather than operationalized using real world case studies. This is mainly because understanding SES dynamics through empirical observation is a major challenge, as modelling SES dynamics is still in the early stage of development (Filatova et al. 2013; Schlüter et al. 2012). Traditional models such as hydrological models (e.g. GWAVA, GLOBWB), agriculture models (e.g. CROPWAT) (Wahaj et al. 2007) and Bayesian models do not consider the interactions and feedbacks among the biophysical and social components. Though some of the modelling approaches can capture the interactions between the variables, understanding the feedbacks through empirical observation is still very challenging. In particular, modelling tools for capturing two-way feedbacks (social to ecological, and ecological to social (Berkes 2011)) are still in their infancy due to complexity (Oreskes 2003), which makes it more difficult to test the meaningfulness of a model as it adds

more processes, variables and uncertainty. Thus, it is highly challenging to understand the feedbacks within the social system, between the social and ecological systems and within the ecological system.

Modelling approaches such as System Dynamics (SD) modelling can incorporate feedbacks at aggregated levels but with the limitation that SD does not capture spatial dynamics of SES across different scales. Though Agent-Based Modelling (ABM) can account for spatial heterogeneity, it is limited to modelling the SES behaviour of individual agents (e.g. households, organisms) (Borshchev and Filippov 2004). Furthermore, ABM requires detailed information and is highly complicated in terms of the accuracy of replicating a less well-known system; it is also difficult to explain and test the unexpected behaviour in real-world trends and patterns (Verburg et al. 2015; Filatov et al. 2013; Letcher et al. 2013).

Developing a coupled component model (CCM) or integrated model (IM) can explore SES dynamics (Schreinemachers and Berger 2011); however, the mismatches of the temporal scale and spatial scale of different individual components often limit the application of this modelling approach (Letcher et al. 2013). For example, the economic components of the model often operate at the global scale; in contrast, hydrological components integrate local processes and heterogeneity (Voinov and Shugart 2013). Thus, because of the high complexity, such types of models are difficult to understand and successful replication of real-world behaviour is rare (Letcher et al. 2013; Voinov and Cerco 2010). Without understanding SES dynamics, operationalization of resilience theory will be limited (Barrett and Constas 2014), and without this, it will be highly challenging to identify how long the social system can afford environmental degradation and the identification of SJOS beyond which humanity will be deprived of basic human needs (e.g. food, health. income, education). Therefore, it is highly crucial to overcome this challenge through unravelling and understanding the relationships within SES while operationalizing SJOS at regional scale.

3.2.1.3. Dealing with uncertainty

Understanding and unravelling the SES is highly connected with reducing the uncertainty of the boundary defined for the regional SES. For example, some studies postulate that increasing variance could be an early warning signal for system instability before moving beyond SOS (Hossain et al. 2017; Dakos et al. 2012; Wang et al., 2012). Other note the system could move beyond SOS without warning (e.g. variance) (Boerlijst et al. 2013; Hasting and Whysham 2010) and rising variance may enlarge the SOS for the SES (Carpenter et al. 2015). Thus, it is essential to understand system behaviour (i.e. what increases the system instability) and how the

system behaves in the long run, prior to quantifying the impacts due to social-ecological changes in order to define the SJOS.

Reducing uncertainty is challenging, mainly due to the gaps in data and current scientific knowledge, which limits understanding feedbacks in SES (Rockström et al. 2009b). Existing modelling approaches also increase the challenges in dealing with the uncertainty of the system. For example, understanding and addressing uncertainty using the ABM or coupled model is very difficult and poorly understood due to the highly complicated structure of the model, which makes it difficult to adapt to the changing interactions of the SES, reproduce simulation results and explore the uncertainties of the system (Letcher et al. 2013). In addition to the limitation of existing modelling approaches, modelling processes such as system definition and structure of model as well as the over-parameterization (redundancy of information) of the model could influence the uncertainty in system understanding.

The original SOS concept used a precautionary approach by setting the boundary at the lower end of uncertainty while defining the SOS at global scale based on available data and existing scientific knowledge. Though the downscaling of the SJOS concept to regional scale could reduce uncertainty due to less heterogeneity and high familiarity with the system compared to larger scales (e.g. national or global scale), data unavailability at regional scale as well as conflicts among stakeholders (e.g. conflict between upstream and downstream water management, or between shrimp farming and rice cultivation) could increase the challenges in dealing with uncertainty. Furthermore, at the regional scale, incorporating individual behaviour such as decisions about shifting livelihood patterns, choice of migration and the way social networks and relationships respond to and interact with changes in SES could bring additional challenges in dealing with SES at regional scale. Thus, incorporating the social systems into the original SOS is essential, but brings additional challenges such as dealing with the uncertain nature of social and ecological systems.

3.3. Systems governance

Systems governance provides transformative knowledge (how to induce change) for transformation to sustainability by integrating perspectives and visions of diverse key decision-makers into defining the SJOS and normative judgments about how societies choose to deal with risk and uncertainty. This operational step includes four key challenges (elaborated in the next section) to operationalize SJOS concept at the regional scale.

3.3.1. Conceptualizing and defining SJOS

3.3.1.1. Conceptualization of SJOS

Prior to operationalizing the SJOS concept at a regional scale, one standard conceptualization and definition of SJOS is essential; it is also possibly one of the major challenges that could arise in making the concept work at policy level. However, rather than trying to provide a guideline for conceptualizing and defining SJOS, this review examines some key advances in order to provide hints about the challenges that may be involved while conceptualizing and defining SJOS.

Rockström et al., (2009) used Holocene as the baseline to define the SOS for humanity at a global scale. However, other than climate, no planetary processes were suitable for human development at Holocene (Vries et al. 2013; Nordhaus 2012). In contrast to the use of multiple boundaries for multiple planetary processes in the original PB, only the net primary production has been used as a measurable planetary boundary at global scale (Running 2012). Furthermore, Vries et al. 2013 emphasised the idea of using both benefits, adverse impacts and spatial aspects of planetary processes such as nitrogen instead of using only the adverse impacts while defining the boundaries. For example, the adverse impacts (e.g. leaching and runoff to surface and ground water) of overusing nitrogen and benefits (essential to raise crops and animals) of nitrogen need to be considered while defining the SOS.

However, all these studies excluded social dimension while defining the SOS for their own case studies. Social dimension was integrated through setting minimum limits for social dimensions (e.g. food, water, energy) in the studies by Dearing et al. (2014) and Cole et al. (2014). Dearing et al. 2014 used system dynamic properties (e.g. linear and non-linear trends, early warning signals) to define the boundaries for the ecological process at regional scale. In contrast, Cole et al. 2014 used available data on national limits and a stakeholders' consultation to define wide ranges of ecosystem processes, similar to the list of indicators used by Rockström et al., (2009). The recent advancement (Hossain et al. 2017) defined SJOS based on both system dynamic properties (envelope of variability) and the consideration of societal impacts for moving beyond the envelope due to changes in SES. However, it excludes the equity and ethical dimensions and conflict over resource exploitation (e.g. shrimp vs. mangrove) in conceptualizing and defining the SJOS. In addition, selected indicators reflect the local context of the case study and are difficult to link with the national and global PB.

3.3.1.2. Setting the boundary

The original PB framework used a precautionary approach while defining and setting boundaries at the lower end of the uncertainty zone, with an argument that a more risk-based approach could be taken by setting the boundaries at the upper end of the uncertainty. Thus, it raises the question of which approach (more or less risk-prone) should be used when defining the boundary.

Scheffer et al. (2009) argued that critical transition in SES should be identified in relation to the societal impacts, though it is difficult to identify how the far the society can afford the social-ecological changes such as conversion of land and withdrawal of water resources. Furthermore, a major challenge is not just to quantify the absolute value of the ecosystem process, but also to consider its function, quality and spatial aspects, as well as the social and cultural value of these ecosystem processes (de Groot et al. 2010).

The discussion on dynamic and static boundary brings another dimension of challenge into the operationalization of SJOS. Though the original PB and all other studies defined fixed boundaries, these defined boundaries are likely to change over time due to technological advancement, resilience and evolution of the system and political and societal agreements.

3.3.2. Incorporating the justice and equity dimension

Factors determining progress towards sustainability futures need to be addressed beyond a place-based, territorial approach in order to include interlinkages between places in terms of flows of ecosystem goods and services (Boillat et al. 2018; Sikor et al. 2013). For example, environmental impacts resulting from to the consumption of goods and services in Switzerland often occur beyond the border, where the product originated (Dao et al., 2018). Shrimp produced in Bangladesh, Thailand and Sri Lanka is mainly consumed in developed countries, whereas the social and ecological impacts of shrimp farming occur largely in the place where shrimp is produced. Though shrimp farming contributes to national and individual (shrimp farmers') economic progress, it imposes negative impacts to agriculture by decreasing agricultural production and increasing poverty at the regional scale (Hossain et al. 2016). Climate change could be another classic example for justice and equity. Setting a global boundary for climate change and allowing this to remain within the boundary for all countries, may undermine the responsibility of polluters (largely currently in industrialised countries) and the right to sustainable development for developing countries inhabitants who have polluted less but may suffer climate change more harshly relative to developed countries. Thus, it has been argued that justice (e.g. the distant impacts of shrimp farming) and equity

(e.g. conflict between shrimp and rice-crop farming) perspectives need consideration when assessing sustainability using the SJOS concept at regional scale (Pasgaard and Dawson 2019; Raworth, 2012).

Advances to represent SJOS at sub-national (Hossain et al. 2017; Dearing et al. 2014) and national (Cole et al. 2014) levels have focused on local economic activities based on production, without incorporating the distant impacts of local consumption, despite wide recognition of the importance of water, land, carbon and other footprints. In contrast, studies based on consumption (e.g. Dao et al. 2018) have focused on ecological boundaries without incorporating the social dimension, raising the need to integrate both social and biophysical boundaries (e.g. Nykvist et al. 2013). Inequalities remain a major challenge to territory-based environmental governance, as certain consumers benefit from goods and services while other people, often located in distant places, experience adverse ecological and social impacts arising from their production. Incorporating the territorial approach into SJOS to ensure the justice and equity dimension raises additional conceptual challenges such as measuring the ecological footprint, avoiding bias towards trade and calculating the energy footprint. Analysis of lower spatial levels such as local scale is more difficult due to inadequate databases and the heterogeneous trade pattern (Wackernagel et al. 2004). For example, similar to global scale, it may be straightforward to calculate the footprint of the total national resource consumed. However, mapping and disaggregation of the total national footprint according to the origin of resource production becomes more complicated because of heterogeneous trade flows; for example, coffee consumed in Switzerland is often produced in various locations across the world. Furthermore, the inability of this approach to capture the effect of land degradation as well as the static measurement of this approach are major challenges to overcome when incorporating the territorial approach into the SJOS concept at regional scale (Wackernagel et al. 2004).

3.3.3. Actors' visions and policy relevance

Though the initial delineation of SOS and SJOS was derived by the scientific community, designing SJOS for SES is often an ethical and political choice, as making the SJOS operational entails the engagement of relevant actors who operate at national and regional scales (Häyhä et al. 2016). Realizing the importance of actors' visions, Pasgaard and Dawson (2019) argued that before designing the SJOS concept, it is important to understand the questions: SJOS for whom? By whom? Who is willing to accept an environmentally safe and socially just space? And who has the power to decide and the will to make the SJOS work? Therefore, designing

SJOS at regional scale needs a transdisciplinary approach aimed at negotiation and integration of actors' visions.

Making SJOS operational at national and local scales is likely to face a diversity of stakeholders' views on target values of sustainability. As the major "aim of the SJOS is to influence public policy", that largely occurs at the national scale (Cole et al. 2014), and as determining a SJOS involves "normative judgements of how societies choose to deal with risk and uncertainty" (Rockström et al. 2009a), there is a need to integrate the perspectives and visions of diverse key decision-makers (Balvanera et al. 2017, Pohl et al. 2010) into defining the SJOS. Therefore, an actor-based transdisciplinary approach that understands the underlying mental models of expectations of change is critical for transformation. Such mental models include stakeholders' concern for a SJOS, the processes they perceive to contribute to environmental stresses and social deprivations, justice and equity principles, and the resources that can be drawn in order to achieve the changes they envisage (Hornik et al. 2016). Hence, setting up social learning spaces and deliberative processes is key to enabling actors to confront the diverse mental models of change that can trigger reflexivity about their own actions and their consequences.

3.4. Visualization and communication

The meaningful translation of scientific research through effective and efficient communication and visualization has been identified as one of the prerequisites for conveying information to end users (e.g. policymakers, consumers) (Zhao 2017; Wong 2012). In particular, studies have shown how the successful negotiation of a global response to climate change depends on the communication of climate science to decision-makers (Elgendi 2017; Pidgeon and Fischhoff 2011). Considering the challenge faced by scientists in explaining climate change to non-specialists, we can assume considerable effort would be required to communicate the SJOS concept, which not only integrates climate science but also expands to other sustainability challenges such as land use change, ocean acidification, food insecurity, poverty alleviation and inequality. Though the initial visualization of SOS (e.g. Rockström et al. 2009) and SJOS (e.g. Cole et al. 2014; Raworth 2012) concepts successfully gained wide interest of academics and policy makers, operationalization of SJOS in terms of visualization requires integrating diverse challenges and complexities (e.g. Cooper and Dearing 2018; Hossain et al. 2017) such as interactions and feedbacks between social and ecological systems at regional scale.

Integration of such diverse disciplines into one concept makes the communication of the SJOS concept highly challenging in terms of meaningful translation and conveying the science and uncertainties as well as the practical implications of the SJOS concept. Furthermore, there is currently no tool to visualize the SJOS concept across different scales.

Therefore, we need to identify communication and visualization strategies for communicating this interdisciplinary and multidisciplinary concept in order to convey a clear and meaningful translation of the science and the practical implications of this concept. Lack of desire, inability and underestimation of communicating this concept to the public could limit the wider diffusion and acceptability of this concept for the decision-making process at regional scale.

4. The opportunities of overcoming these challenges

We have identified (SI Table 2) opportunities that will emerge for overcoming challenges to operationalizing the SJOS concept at regional scale. In general, the SJOS concept provides: (1) a powerful metaphor and communication tool for the transition to sustainability at regional scale; (2) a contribution to the comparative and distributional dimensions of social transformation in achieving sustainability with regards to the global commons; 3) support for understanding the complex governance of social-ecological flows, societal consequences and shared responsibilities for regional and global sustainability; and (4) a basis for assessing regional contribution to global planetary boundaries using the social-ecological flows concept and ethical dimension of sustainability.

In summary, the SJOS concept not only provides a basis for comparing the development progress within and across the regions to allocate resources (e.g. sharing transboundary water resources) and share responsibilities (e.g. emissions caps and allowance), but also for exploring and designing pathways for regional sustainability within the limits of SES adaptive capacity. In particular, the Sustainable Development Goals (SDGs) 2030 offer the opportunity to explore development pathways through integrating the three pillars (economic, social and environmental) of sustainability, without highlighting the limits beyond which, SES moves towards an unsustainable state. Therefore, this novel concept complements the SDGs 2030 through integrating the three pillars of sustainability and offering a delineation of SES boundaries within which we can transform our regions towards sustainable development. Furthermore, the idea of a SJOS in terms of being within the ecological boundaries of a place, and just, in terms of being socially just, complements the idea of the

732 zero poverty goal (Target 1) of SDGs, ensuring that those who have escaped poverty do not
733 fall back into poverty, while alleviating poverty across different scales.
734
735 This article also provides (SI Table 2) an overview of the opportunities that
736 could arise for overcoming challenges in operationalizing the SJOS concept at regional scale.
737 A selection of indicators that follow national and international rules and regulation, and social
738 norms could offer the opportunity to monitor short and long-term social progress (e.g. SDGs,
739 international law and agreements, regional and national targets) and ecological degradation.
740 This will enable the mapping of regional progress, contribution and share of burdens on
741 national and planetary boundaries through linking global to regional and regional to global
742 problems.

743 The conceptualization and the definition of a SJOS concept, considering actors' visions
744 and policy, could offer co-development of pathways for sustainable development and increase
745 the impact of SJOS concept at policy level. For example, this could be more policy-relevant if
746 we explore pathways of adaptation or water resources management practices (e.g. dams or
747 sharing water between upstream and downstream use) and the optimum ways of achieving
748 SDGs, and the drivers for which the SES may transgress the SJOS, beyond which society may
749 be deprived of basic human needs (e.g. education, food security, health). This could also
750 provide a comprehensive overview of data needs and gaps at regional scale, as this concept
751 integrates a wide range of indicators that cover the three (social, economic and ecological)
752 sustainability pillars. Ultimately, overcoming data unavailability challenges at the regional
753 scale could support the improvement of the comparative dimension of the SJOS concept,
754 which in turn complements the SDGs through accounting for regional differences and
755 inequalities (UN 2015). Ultimately, this concept can help account for regional differences in
756 order to ensure regions that meet their entire population's basic human needs do not fall into
757 deprivation, while making progress in other regions.
758 In addition to the opportunities identified in SI Table 2 for understanding and
759 unravelling the SES, this concept could enable an understanding of the resilience of SES in
760 order to explore how much shock the SES can absorb and how far society can afford the
761 changes in SES. Ultimately, the improvement in understanding of the SES at regional scale will
762 reduce the risk and complexities of making decisions under uncertainty.
763 Inclusion of a justice and equity dimension in the SJOS not only incorporates the distance
764 impacts of local consumption, but also provides a basis for reducing inequalities within and
765 across the regions. For example, the SJOS concept, based on the distance impact of coffee
766 consumed in developed countries, provides a justice and equity perspective for compensating

the societal impacts experienced in the regions where the coffee has been produced but not consumed. Inclusion of gender aspect into SJOS concept may help reduce inequalities and strengthen women and youth influence over decision-making on use of land and natural resources and their benefits.

Furthermore, a similar approach could also provide a tool for negotiation to resolve conflicts among stakeholders at regional scale. For example, at the Ganges river basin, the sharing of water resources could be based on the consideration of the SES across different regions. In particular, this offers the opportunity to explore water availability and deprivation across different regions, and how changing SES dynamics could influence water security, which is often linked to ecological degradation, which in turn exacerbates human deprivation. Ultimately, an equitable distribution of water resources would ensure all regions have sufficient water to thrive.

5. Concluding remarks

In this paper, we reviewed empirical studies on SJOS concepts and developed a conceptual framework to identify the challenges (conceptual and methodological challenges) in operationalizing the SJOS concept for regional SES. We also discussed the opportunities for overcoming the challenges for the transformation to sustainability within the limits of SES across different scales. The operational framework developed in study can be used in assessing sustainability of SES and operationalizing the concepts such as the SJOS and limits to sustainability for regional SES.

We limited our focus by not exploring methodological approaches to overcome these challenges. Though some of the operational steps such as communication and system understanding indirectly may provide transformation knowledge (how to induce change), answering the question how to induce change is beyond the scope of this paper.

Although the SJOS concept has gained attention in academia and policy, researchers are confronted with a range of challenges, without overcoming which, the acceptability of this concept may be limited in the decision-making process. In particular, dealing with this concept requires to integrate diverse disciplines and societal perspectives, which makes the operationalization of this concept complicated, though it also provides a base for addressing sustainability challenges in an integrative and comprehensive way.

In order to do so, researchers need to improve methodological aspects to understand and unravel the SES, and to incorporate the justice and equity dimension into the SJOS concept while accounting for SES dynamics. Emphasis is needed on how we can meaningfully translate and derive practical implications by overcoming the challenges of visualizing and

communicating the SJOS concept to decision-makers. In general, operationalizingthe SJOS concept is very challenging, but overcoming these challenges is crucial as these offer opportunities for the transformation to sustainability at a regional scale.

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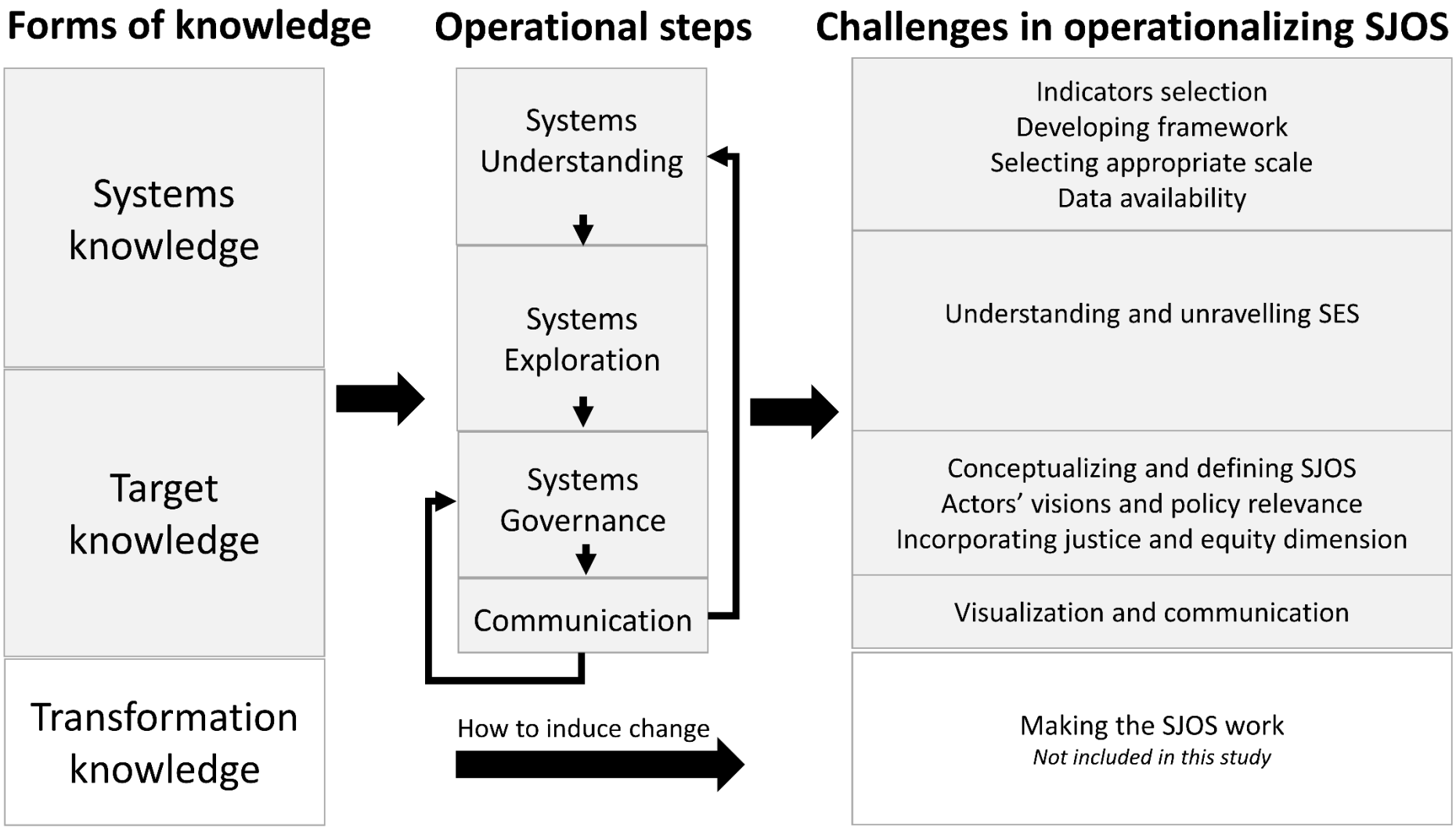

Figure 1 A conceptual framework for identifying the challenges in operationalizing SJOS for regional social-ecological systems