SI Table 1. Overview of the scale, approaches, limitations and challenges in the reviewed key papers which operationalized the SOS and SJOS concepts.

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| --- | --- | --- | --- | --- | --- | --- |
| **SL** | **Study** | **Scale**  **(Global/National/Regional)** | **Boundary Dimension**  **(Ecological/Social/Social-ecological)** | **Approaches** | **Limitations** | **Challenges** |
| 1 | Rockström et al., 2009a and Rockström et al., 2009b | Global | Ecological | The SOS concept introduced through the planetary boundaries (PB) framework.  Identified nine planetary boundaries based upon current scientific understanding | Exclusion of social dimension  Exclusion of interactions and feedbacks between SES | Downscaling the nine planetary boundaries to regional scale |
| 2 | Raworth (2012) | Global | Social-ecological | Inclusion of social dimension into the PB framework | Exclusion of interactions and feedbacks between SES | Downscaling of social and ecological indicators to regional scale |
| 3 | Nykvist et al., 2013 | National | Ecological | Seven indicators used to define the SOS using the best available science and the precautionary principle for Sweden | Exclusion of social dimension  Exclusion of interactions and feedbacks between SES | Inclusion of social dimension  Integrating the interactions and feedbacks within ecological, social and between social and ecological systems. |
| 4 | Dearing et al., 2014 | Regional | Social-ecological | System behaviour and regional social norms (nationally or internationally agreed minimum standards) to define the SJOS in two Chinese case studies | Exclusion of interactions and feedbacks between SES, equity and justice, actors’ visions | The proposed system behaviour framework is challenging to apply for other variables such as rainfall.  Integrating the interactions and feedbacks within ecological, social and between social and ecological systems. |
| 5 | Cole et al., 2014 | National | Social-ecological | Downscaled the SJOS framework for South Africa by including 20 social and ecological indicators  Engagement of actors in selecting and defining national boundaries. | Exclusion of justice and equity in terms of flows of ecological goods and services  Exclusion of interactions and feedbacks between SES | Downscaling the indicators to regional scale  Integrating the interactions and feedbacks within ecological, social and between social and ecological systems. |
| 6 | Mace et al., 2014 | Global | Ecological | Revision of boundary for biodiversity based on the genetic library of life; functional type diversity; and biome condition and extent | Single indicator based boundary and exclusion of other ecological boundaries and social dimension.  Exclusion of interactions and feedbacks between SES | Downscaling of this approach, even using the single indicator (biodiversity), is challenging due to data unavailability at regional scale  Incorporating actors visions, equity and justice |
| 7 | Steffen et al., 2015 | Global | Ecological | Revised and updated the PB framework by including the zone of uncertainty: Green zone (SOS), yellow: zone of uncertainty (increasing risk), and red is the high-risk zone  Geographical heterogeneity of 4 control variables | Exclusion of social dimension  Exclusion of interactions and feedbacks between SES | Downscaling of PB (revised) framework at regional scale  Incorporating actors’ visions, equity and justice  Integrating interactions and feedbacks between SES |
| 8 | Hoornweg et al., 2015 | Regional | Social-ecological | Operationalization of the SJOS concept from an urban perspective  Inclusion of social indicators based on SDGs and data availability  Assessment of PB for five cities: Toronto, Shanghai, Sao Paulo, Mumbai, and Dakar | Spatial heterogeneity  Data driven  Exclusion of justice and equity in terms of flows of ecological goods and services | Contextualization and operationalization of this approach in other urban and rural areas where data gaps are higher.  Capturing interactions and feedbacks between SES |
| 9 | Carpenter et al., 2015 | Regional | Ecological | Operationalization of SOS in three ecosystems: lake eutrophication, harvest of a wild population, and yield of domestic herbivores on a rangeland  Mathematical equation-based simulations, mainly using variance as an output indicator | Exclusion of social dimension, interactions and feedbacks between SES | Connecting this approach with original PB  Incorporating actors’ visions, equity and justice  Integrating interactions and feedbacks between SES |
| 10 | Teah et al., 2016 | Regional | Ecological | Downscaling of PB to Semi-Arid Ecosystems  Top-down approach using environmental monitoring data, and a bottom-up approach using knowledge from local perception | Exclusion of PB such as climate change  Exclusion of social dimension, interactions and feedbacks between SES | Integrating interactions and feedbacks between SES  Visualization of SJOS |
| 11 | Hossain et al., 2017 | Regional | Social-ecological | System dynamics modelling to operationalize the SJOS concept for regional SES (Agriculture: Bangladesh delta)  Interactions and feedbacks between SES  Scenario based exploration to investigate at what point SES may move beyond a SJOS | Understand the general behaviour of the systems  Limited social indicators such as GDP, income, subsidy considering the social-ecological settings  Limited to well-known challenges while exploring the scenarios | Incorporating actors’ visions, equity and justice  Quantifying the behaviour of the system  Spatial heterogeneity and cross-scale dynamics  Visualization and communication of SJOS |
| 12 | O’Neill et al., 2018 | National | Social-ecological | Downscaled planetary boundaries for over 150 nations  Spatial heterogeneity of PB and social needs provides the comparability dimension of the SJOS concept  Policy implications for global and national scale sustainable resource use in the context of basic human needs. | Exclusion of justice and equity in terms of flows of ecological goods and services  Exclusion of interactions and feedbacks between SES | Operationalizing at regional scale.  Incorporating actors’ visions, equity and justice  Integrating interactions and feedbacks between SES |
| 13 | Cooper and Dearing 2018 | Regional | Social-ecological | Operationalization of the SJOS concept for regional SES (Chilika lagoon, India)  System dynamics modelling to integrate interactions and feedbacks between SES (Fishery)  Identified interacting pathways to sustainable futures by exploring range of uncertainty at regional scale | Exclusion of actors’ visions, equity and justice  Limited social indicators (e.g. price, income, livelihood cost) in the context of the case study (fisheries) | Operationalizing and contextualizing for other SES  Incorporating actors’ visions, equity and justice  Spatial heterogeneity and cross-scale dynamics  Visualization and communication of SJOS |
| 14 | Heck et al., 2018 | Global and National | Social-ecological | Use of PB framework to quantify land use options for staying with SOS.  Defining upper bounds of carbon storage, biodiversity conservation  Model based trade-offs considering environmental and developmental (e.g. SDGs) goals | Exclusion of social dimension  Exclusion of interactions and feedbacks between SES  Limited to SOS | Integrating feedbacks between SES  Incorporating actors’ visions which varies across different scales  Incorporating equity and justice |
| 15 | McLaughlin 2018 | Regional | Ecological | Operationalization of SOS at regional scale (county and river basic)  Use of DPSIR framework  Delineation of regional boundaries for land-system change, freshwater use, phosphorus flows, nitrogen flows | Exclusion of social dimension  Exclusion of interactions and feedbacks between SES  Limited to SOS  Exclusion of PB such as climate change | Integrating interactions and feedbacks between SES  Incorporating actors’ visions  Incorporating equity and justice  Applying this approach from individual sub basins to a large basin. |
| 16 | Dao et al., 2018 | National | Ecological | Setting limits at country level: Switzerland  Territorial and footprint perspectives  Engagement of actors to validate boundaries and to provide policy recommendations.  DPSIR framework as a base for selecting indicators | Exclusion of social dimension, interactions and feedbacks between SES | Operationalizing this approach at regional scale.  Integrating interactions and feedbacks between SES  Visualization of SJOS |
| 17 | Roy and Pramanic 2019 | National | Social-ecological | Indicators related to monitoring and implementation of the targets of the UN SDG 6 in India.  Analysis of historical and future trends | Limited social indicators  Exclusion of indicators used in original SOS and SJOS  Exclusion of justice and equity in terms of flows of ecological goods and services  Spatial heterogeneity | Downscaling to regional scale  Capturing interactions and feedbacks between SES  Incorporating actors’ visions  Incorporating equity and justice |

**SI Table 2:** Challenges and opportunities for operationalising the safe and just operating space at regional scale

|  |  |
| --- | --- |
| **Challenges** | **Opportunities** |
| Selecting indicators | * Indicators to monitor short and long-term social (e.g. SDG) progress and ecological degradation * Translating global issues into regional issues and regional contributions to global problems |
| Developing frameworks | * Integrating social, ecological and economic aspects * Providing basic ground for guiding the conceptualization, implementation and monitoring of SJOS * Comparability and transferability across regions * Regional barometer for sustainable development |
| Selecting appropriate scale | * Sustainability transformations across spatial and temporal scales * Monitoring national and regional performances |
| Data availability | * Utilization of existing information and science based on best available knowledge * Identifying gaps and needs for monitoring short and long-term progress |
| Understanding and unravelling interactions and feedbacks  (within ecological, within social and between social and ecological systems) | * Systematic approach for policymaking * Understanding of system behaviour in parallel with scenario analysis * Integrating social, economic and social aspects while developing policies for development * Understanding of human-nature relationships and dynamics across scales * Understanding slow and fast variables and gradual long-term changes when preparing for perfect storm and avoiding societal collapse * Shock absorbing capacity, re-organization, development and sustainability of the system * Fostering the understanding of human behaviour in response to social, environmental and economic changes * Dealing with uncertainty   • Sustainable development pathways, trade-offs and synergies  • Increasing range of knowledge for learning and problem-solving  • Increasing ability to predict future changes |
| Conceptualizing and defining SJOS | * Defining acceptable and unacceptable risks * Policy relevance and reducing bias |
| Incorporating justice and equity dimension | * Fair and equitably shared responsibility and resources * Barometer for resolving conflicts and negotiation * Improving our understanding of inter-regional fluxes * Reducing inequalities with and across region |
| Actors’ visions and policy relevance | * Political and socially legitimate targets * Inclusion of global (e.g. SDGs) and national policies * Co-development of transformation pathways |
| Visualization and communication | * Transferability of the SJOS concept * Social and political acceptance of the SJOS concept * Increasing the possibility of using the SJOS concept for decision making process * Metaphor and communication tool for regional equity and sustainability |

SI Table 3. Overview of how the indicators of original planetary boundary approach (Rockström et al., 2009a) are operationalized in the reviewed key papers.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **SL** | **Study** | **Climate change** | **Ocean acidification** | **Stratospheric ozone depletion** | **Nitrogen cycle** | **Phosphorus cycle** | **Freshwater** | **Changes in land use** | **Biodiversity** | **Atmospheric aerosol loading** | **Chemical pollution** |
| 1 | Rockström et al., 2009a | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Not yet quantified | Not yet quantified |
| 2 | Raworth (2012) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Not yet quantified | Not yet quantified |
| 3 | Nykvist et al., 2013 | ✓ |  | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |  |  |
| 4 | Dearing et al., 2014 |  |  |  |  |  | ✓ (Water quality and regulation) | ✓ (Soil stability) |  | ✓ (Air quality) |  |
| 5 | Cole et al., 2014 | ✓ | ✓  (Marine Harvesting) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓  (Air pollution) | ✓ (Eutrophication) |
| 6 | Mace et al., 2014 |  |  |  |  |  |  |  | ✓ |  |  |
| 7 | Steffen et al., 2015 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ (Change in  biosphere  integrity) | ✓ Not yet quantified | ✓ Introduction  of novel entities (Not yet quantified) |
| 8 | Hoornweg et al., 2015 | ✓ |  |  | ✓ |  | ✓ | ✓ | ✓ |  | ✓ |
| 9 | Carpenter et al., 2015 |  |  |  |  | ✓ |  |  |  |  |  |
| 10 | Teah et al., 2016 |  |  |  | ✓ | ✓ | ✓ | ✓ |  | ✓ |  |
| 11 | Hossain et al., 2017 | ✓ |  |  |  |  | ✓ | ✓ |  |  |  |
| 12 | O’Neill et al., 2018 | ✓ |  |  | ✓ | ✓ | ✓ | ✓ |  |  | (Ecological Footprint and Material Footprint) |
| 13 | Cooper and Dearing 2018 | ✓ |  |  |  |  | ✓ |  |  |  |  |
| 14 | Heck et al., 2018 | ✓  (Carbon pool) |  |  |  |  | ✓ | ✓ | ✓ |  |  |
| 15 | McLaughlin 2018 |  |  |  | ✓ | ✓ | ✓ | ✓ |  |  |  |
| 16 | Dao et al., 2018 | ✓ | ✓ |  | ✓ | ✓ |  | ✓ |  |  | ✓ |
| 17 | Roy and Pramanic 2019 |  |  |  |  |  | ✓ |  |  |  |  |

SI Table 4. Overview of how the indicators of SJOS concept (Raworth 2012) are operationalized in the reviewed key papers.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| SL | Study | Water | Income | Education | Resilience | Voice | Jobs | Energy | Equity | Gender equality | Health | Food |
| 1 | Rockström et al., 2009a |  |  |  |  |  |  |  |  |  |  |  |
| 2 | Raworth (2012) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 3 | Nykvist et al., 2013 |  |  |  |  |  |  |  |  |  |  |  |
| 4 | Dearing et al., 2014 | ✓ | ✓ | ✓ |  |  | ✓ |  |  |  | ✓ | ✓ |
| 5 | Cole et al., 2014 | ✓ | ✓ | ✓ |  |  | ✓ | ✓ |  |  | ✓ | ✓ |
| 6 | Mace et al., 2014 |  |  |  |  |  |  |  |  |  |  |  |
| 7 | Steffen et al., 2015 |  |  |  |  |  |  |  |  |  |  |  |
| 8 | Hoornweg et al., 2015 | ✓ | ✓ |  |  |  |  | ✓ | ✓ |  |  |  |
| 9 | Carpenter et al., 2015 |  |  |  |  |  |  |  |  |  |  |  |
| 10 | Teah et al., 2016 |  |  |  |  |  |  |  |  |  |  |  |
| 11 | Hossain et al., 2017 | ✓ | ✓ |  |  |  |  |  |  |  |  | ✓ |
| 12 | O’Neill et al., 2018 | ✓ | ✓ | ✓ |  |  | ✓ | ✓ | ✓ |  | ✓ | ✓ |
| 13 | Cooper and Dearing 2018 |  | ✓ |  |  |  |  |  |  |  |  |  |
| 14 | Heck et al., 2018 | ✓ |  |  |  |  |  |  |  |  |  | ✓ |
| 15 | McLaughlin 2018 |  |  |  |  |  |  |  |  |  |  |  |
| 16 | Dao et al., 2018 |  |  |  |  |  |  |  |  |  |  |  |
| 17 | Roy and Pramanic 2019 | ✓ |  |  |  |  |  |  |  |  |  |  |