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SPECIAL FEATURE: ORIGINAL ARTICLE

Networks of Action Situations in Social-Ecological Systems Research

Unpacking dynamics of diverse nested resource systems through a diagnostic approach

Hita Unnikrishnan[1,2] · Maria Katharina Gerullis[3] · Michael Cox[4] · Harini Nagendra[2]

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Abstract

The social–ecological systems (SES) framework (Ostrom 2009, Science. 325(5939):419–22) typologically decomposes SES characteristics into nested, tiered constituent variables. Yet, aligning the framework's concepts of resource system (RS) and resource unit (RU) with realities of individual case studies poses challenges if the underlying SES is not a single RS, but a mid to large-scale nested RS (NRS). Using a diagnostic approach, we describe NRSs—and the activities and networks of adjacent action situations (NAAS) containing them. An NRS includes the larger RS and multiple interlinked semi-autonomous subsidiary RSs, each of which support simultaneous, differently managed appropriation of individual RUs. We further identify NAASs operating within NRSs in two diverse empirical cases—networks of lake systems in Bengaluru, India and German wheat breeding systems—representing a lever towards understanding transformation of SESs into sustainable futures. This paper contributes towards unpacking and diagnosing complexities within mid to large-scale RSs and their governance. It provides a generalizable, rigorous approach to SES case study analyses, thereby advancing methods for synthesis in sustainability science.

Keywords Social–ecological systems framework (SESF) · Nested resource systems (NRS) · Networked adjacent action situations (NAAS) · Diagnosis · Case study analysis

Introduction

Effective policy-making around complex social–environmental challenges requires development of mid-range theories straddling generality, realism, and precision across diverse explanatory variables (Meyfroidt et al. 2018). Middle range theories are "contextual generalisations that describe chains of causal mechanisms explaining a well bounded range of phenomena, as well as conditions that enable, trigger, or prevent these causal chains" (Meyfroidt 2016). A diagnostic approach has been long considered effective in developing such contextual generalisations (Cox 2011). The Institutional Analysis and Development framework (IADF) (Ostrom 1990) and its ecologically grounded successor (Cole et al. 2019a; b), the Social Ecological Systems Framework (SESF) (McGinnis and Ostrom 2014; Ostrom 2009) are powerful tools in this context, at the core of which lies the concept of action situations (ASs). Articulated in later versions of the SESF (Ostrom and Cox 2010; Cole et al. 2019a, b), the AS is a complex of actor–resource interactions—influenced by four key components (or first-tier components of the SESF): Resource Systems (RSs), Resource Units (RUs), Governance Systems (GSs) and Actors (As). ASs represent the space where policy decisions are devised based upon the actor's relative positions within the complex as well as the various rules that they are constrained or enabled by (McGinnis 2011). A focal AS represents patterns of interactions amongst actors and ecosystem resources within the system of interest. These interactions include social and

Handled by Christian Kimmich, Institut fur Hohere Studien-Institute for Advanced Studies, Austria.

✉ Hita Unnikrishnan
h.unnikrishnan@sheffield.ac.uk

1 Urban Institute, The University of Sheffield, ICOSS, 219, Portobello, Sheffield S1 4DP, UK

2 Centre for Climate Change and Sustainability, Azim Premji University, Burugunte Village, Sarjapur Hobli, Anekal Taluk, Bengaluru, Karnataka 562 125, India

3 Institute for Food and Resource Economics, University of Bonn, Nußallee 21, 53115 Bonn, Germany

4 Department of Environmental Studies, Dartmouth College, Hanover, NH, USA

ecological components, each of which can further be decomposed into smaller elements, as well as be situated within the context of broader aggregations (McGinnis 2011). Despite their utility, challenges in applying the IADF and SESF persist, particularly from the perspective of mid-large-scale social-ecological systems (SES) (Villamayor-Tomas et al. 2020; Epstein et al. 2020; Cole et al. 2019a, b; Partelow 2018; Thiel et al. 2015), due to a gap in developing consistent techniques to interpret and operationalize the large number of variables contained within them (Cox 2014; Leslie et al. 2015; Delgado-Serrano and Ramos 2015; Cumming et al. 2020).

SES challenges further consist of the need to acknowledge and address multiple, interdependent ASs where the outcome of one AS can influence trajectories or outcomes of other ASs. This phenomenon has been explained through the networks of adjacent action situations (NAASs) concept developed by McGinnis (2011). Expanding upon the concept of ASs, at the core of the NAASs lie interactions between the four first-tier components of the SESF described earlier. However, studies have pointed out (Cox 2008; Cox et al. 2020; Hinkel et al. 2015; Vogt et al. 2015; Epstein et al. 2013) that two of these components: the RS and RU remain insufficiently decomposed, challenging the utility of applying the NAAS concept to mid-large-scale SESs.

In this paper, we engage with these two gaps—lack of consistency in applying the SESF and the linked concern of insufficient decomposition of RS and RU. We do this by (a) introducing the concept of nested resource system (NRSs) to negotiate complexity of RS–RU interactions, (b) developing a diagnostic approach to applying the NRS within mid-large-scale SESs, and (c) identifying spatially situated NAASs operating within NRS. We focus explicitly and strategically on the RS and RU components of the SESF. We then provide a diagnostic tool that enables a standardised approach to describing and analysing SESs, both from the perspective of smaller, well-defined SESs as well as mid-large-scale NRS. We demonstrate the applicability of our diagnostic process through comparison across two diverse and distinct systems—networks of lakes in south Indian Bengaluru (Unnikrishnan et al. 2016, 2020) and German winter wheat breeding systems (Gerullis et al. 2021).

The context

Application of the SESF to cases requires a three-tiered process—(a) selecting the focal level of analysis; (b) selecting variables to be measured and the implementation of indicators for those variables (data collection and analysis), and (c) communicating results of the analysis across research communities through a common base of shared terms (McGinnis and Ostrom 2014). In mid-large-scale SESs, one often finds that it is difficult to both draw systemic boundaries as well as specify which components of the SES become the RS and RU and in what context. We argue that this challenge arises because mid-large-scale SESs are inherently nested wherein multiple SESs may exist within each other and are bounded by a larger SES, while not necessarily being linked or networked with each other. This observation was first articulated by Cox (2010, 2014) in his application of the SESF to the Taos acequia irrigation system.

As an example, if we consider the Yellowstone National Park as our system of interest (and therefore the RS), this does not automatically imply that other components of the park exist solely as RUs within that RS. Yellowstone National Park contains multiple potential SESs nested (but not necessarily networked with reference to how system boundaries are defined, or the question being investigated) within it—lakes, rivers, grasslands, calderas, that may or may not be hierarchical in their organisation with reference to the park. Therefore, there is a need to explicitly decompose the RS and RU into possible further subcomponents (Cox 2010, 2014). Multiple RUs and RSs may be involved in equally numerous ASs; further, diverse institutional arrangements may affect multiple ASs simultaneously (Villamayor-Tomas et al. 2015). NAASs operating in such SESs are thus usually scattered not just along societal and institutional dimensions, but also along spatial and ecological ones.

Several approaches to addressing these challenges have been proposed—for example, the addition of a seventh core subsystem category to the SESF—that of ecological rules, allowing analysts to incorporate ecologically derived knowledge into their cases (Epstein et al. 2013). Oberlack et al. (2018) advance the idea of telecoupled RS which refer to RS connections across multiple SESs spread across large distances. Cole et al. (2019a; b) defines processes by which social, ecological, and institutional factors interact across ASs producing social–ecological outcomes, through combining the SESF with the IADF (Cole et al. 2019a; b). Schlüter et al. (2019a; b) have extended the NAAS approach to include explicit consideration of relations that exist between human and non-human entities; in other words, between social and the ecological components of the SES. In doing so, they propose the Social Ecological Action Situation (SEAS) framework, which recognises three distinct forms of ASs, namely the Social AS, Ecological AS, and the Social–ecological AS (Schlüter et al. 2019a; b). Möck et al. (2019) propose that spatial scales, temporal change within systems, and resource linkages may be integrated through an approach of layering ASs as an analytical technique in applying the IADF (as opposed to the conventional technique of comparing temporally and spatially fixed aspects of the ASs).

We argue that while each of these approaches add a lot of value, they do not, however, engage with the root challenge of reconciling decomposition of the RS and RUs. The concept of telecoupled RSs (Oberlack et al. 2018) while coming close to this decomposition does not engage with the idea that multiple systems can exist embedded within each other but might not always be connected in their processes and functions—consider, for example, our earlier discussion of the Yellowstone National Park. This means that NAASs operating within these first-tier components remain spatially aggregated, implying that the links between RSs and their spatial dimensions still need to be explicitly recognized. Further, an analyst applying the SESF with the objective of comparing across diverse cases against a broader goal of generating middle range theories, would need a standardised approach towards unpacking and describing the complexity of their cases both from the perspective of a decomposed RS and RUs as well as the complex array of NAASs that emerge from these contexts.

To address these gaps, we first articulate in greater detail the idea of NRS. We then build upon and expand the diagnostic procedure developed by Hinkel et al. (2015) to include considerations of NRS. This distinction allows us to account for multiple, simultaneously occurring NAASs that collectively give rise to SES outcomes.

Nested resource systems (NRS)

The idea of NRS is highly relevant to dynamics of mid-large-scale SESs. In these contexts, one cannot assume that there are distinctive or easily defined RSs and RUs. Rather, there can be multiple RSs, and each of these RSs can act as RUs depending upon the context within which they are being investigated. For example, let us consider a system represented in its entirety by multiple spatially connected lakes. Traditionally, we would imagine the entire lake system to be the RS and individual lakes within that system to be RUs. However, each individual lake is also capable of providing RUs such as fish, water, or pasturage on its own, thus allowing it to simultaneously function as a RS. Resource flows in this system can occur through multiple pathways—within an individual lake (for example, pasturage or harvesting fish from a lake), between two individual lakes in a network (for example water overflowing from one lake into the next via channels connecting the two), or across the entire network of lakes (for example, a system of water flows or the mobility of fish across the entire network). RUs too may be drawn at any of these levels—one can withdraw water from a single lake or across the system, while fishing or grazing livestock can occur only at the level of individual lakes. If we were to imagine the entire network of lakes to be our RS and individual lakes to be RUs, this distinction is not captured effectively. To address this discrepancy, we propose the idea of the nested resource systems (NRS)—conceptualised through Fig. 1. Highly relevant to mid-large-scale systems whose boundaries are not so easily defined, we propose that NRS may be considered as a complex of several individual semi-autonomous subsidiary RSs that may or may not be connected through physical connections. Each subsidiary RS can both provide RUs from the perspective of the NRS but is equally capable of acting as a standalone

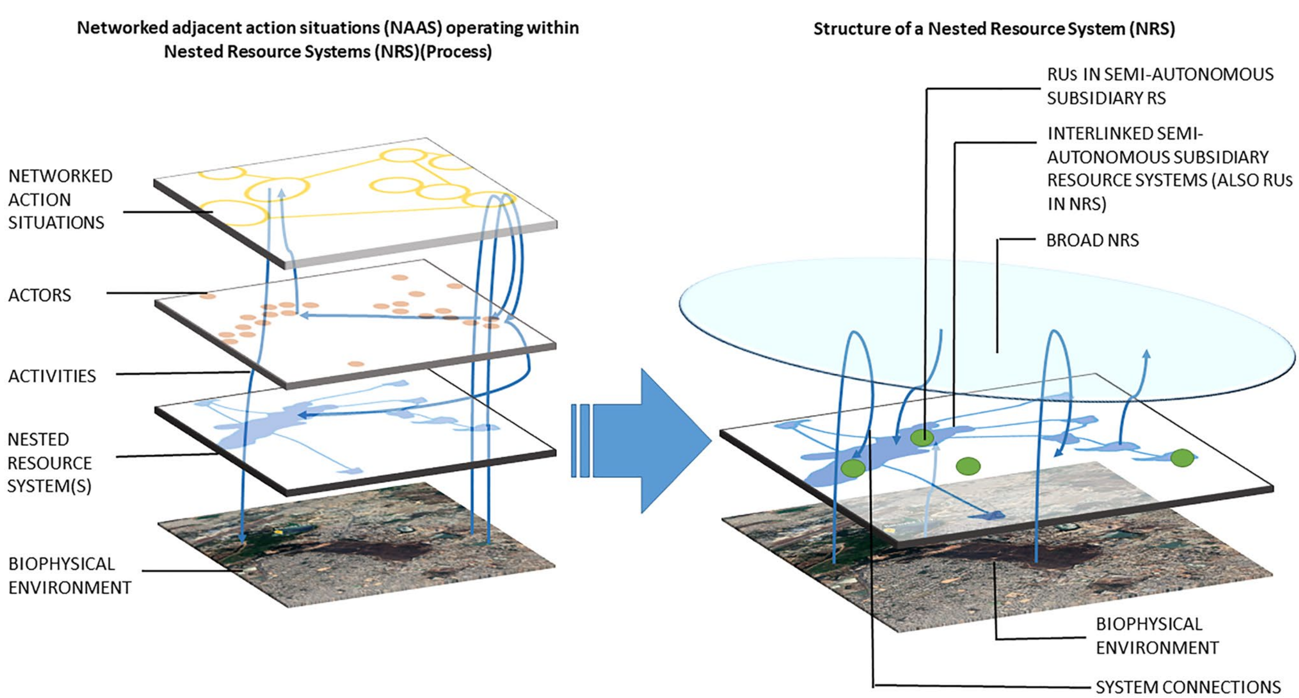

Fig. 1 Structure of an NRS with NAASs operating within it

RS (thus semi-autonomous). There are system connections between different subsidiary RSs. These may come about by biophysical structure such as elevation gradients, or social structures like supply chains when seeds are bred, multiplied and sold as farming input in plant breeding systems. Activities, embedded in ASs can occur separately or simultaneously at four different spatial locations: (a) within the subsidiary RSs, (b) across individual RSs, (c) between the subsidiary RSs and the overall NRS, and (d) within the overall NRS. These ASs can occur across different levels of the NRS, and the outcome of any AS is likely to influence other ASs at any level of the NRS, causing spatially significant adjacencies. Actors operate across the NRS, leading to NAASs, where outcomes of individual ASs occurring at any one level can influence and be influenced by other ASs occurring at other levels. It is important to note that the NRS is situated within its biophysical environment and has multiple (not necessarily linked) components which when taken together define the SES.

The diagnostic approach

To operationalise the concept of a NRS in the context of studying diverse SESs, we first developed a diagnostic protocol to logically unpack different components of a NRS and the NAASs within them that lead to SES outcomes. This diagnostic process was developed through a series of iterative discussions and deliberations amongst the research team drawing on our varied expertise and contextual knowledge of diagnostic protocols and mid-large-scale SESs. Like its use in healthcare, a diagnostic approach can tease out complexity within a SES as well as address the panacea problem (Frey and Cox 2015; Young et al. 2018). It allows the researcher to examine individual characteristics of a problem to identify governance arrangements that may best be suited towards addressing those characteristics (Young 2002, 2010). Diagnosis identifies underlying causes of a problem and works on the principle that addressing the problem would require intervention at causal levels (Cox 2011). It typically involves asking and answering a series of questions about the system such that subsequent questions build upon and add to information presented by previous ones (Berkes 2007; Ostrom 2007; Frey and Cox 2015).

Like the SESF, diagnosis allows typological decomposition of a complex system into its individual components allowing the researcher to unpack non-linear webs of relationships built by individual variables in SESs. It allows the construction of multi-level theories guided by similarities and differences between systems at multiple levels of specificity (Frey and Cox 2015). Such theories can then be used to provide some degree of generalizability and predictability to generate useful prescriptions on interacting with complex SESs (Cox 2011) and in the longer term, enable the creation of middle range theories.

Hinkel et al. (2015) establish a diagnostic procedure by providing a sequence of questions to facilitate stepwise interpretation and application of the SESF across diverse cases. The approach as outlined by them serves as a valuable starting point for this paper due to the following reasons. First, the approach explicitly focuses on RS and RU, due to their role in facilitating focal ASs and therefore the starting point towards applying the SESF to a given case (McGinnis and Ostrom 2014). Hinkel et al. (2015) advance the idea that the appropriation of an AS is inclusive of actors performing activities that depend upon a common stock and further subtract from it. Thus, the diagnostic tool they propose explicitly focuses on activities affecting the RU, allowing for the diagnosis of complex conditions within the SES such as multiple, overlapping, and heterogeneous actors and governance regimes. This is important because it has been shown that defining a stock as a collective good is not very effective largely because a stock by itself is not subtractable—it only becomes subtractable in relation to the activity associated with it (Hinkel et al. 2015). Subtractability as a characteristic is therefore only relative to the activity being performed in relation to the SES, while the property of excludability is related to actors performing the activity.

We acknowledge that ASs can take a wide range of incentive structures within natural resource governance and can include forms of cooperation, conflict, or indifference (Bruns and Kimmich (2021) characterise these through a game theoretical approach as win–win, discord, and threat, with exchange, coordination, and independence as their primal archetypes), and it remains up to the researcher to determine the nature of the incentive structure associated with the SES challenge they are investigating.

Our diagnostic process builds on these premises and begins with identifying broad social ecological challenges that the analyst wishes to address, the research question as relating to the identified challenge/s and the specific SES or NRS that they engage with. We then provide a schematic that guides the analyst towards identifying assumptions behind the outcomes they envision, and a series of questions designed to unpack the complexity of RS and RU variables within the identified SES or NRS in relation to the research question they have identified. The schematic follows on to guide the analyst towards identifying NAASs, the spatial dimensions within which they occur, and outcomes that are generated as a result, all within the system of interest, bounded by the research question and level of analysis. These outcomes are then linked to the research question posed by the researcher, external influencing variables, and further on back to the broad SES challenge/s that they have engaged with. At various stages of the diagnostic process, we provide checkpoints that allow the analyst to ascertain whether their case study may be interpreted using the frames we provide. We do this so that focus remains on outcomes relating to SEASs that occur within SESs/NRS. Figure 2a–c outlines the diagnostic procedure we follow towards analysing and interpreting our cases. We exclude purely social outcomes from this diagnostic process because our focus is on NRS and changes within the RS usually occur because of social–ecological or purely ecological processes. Of course, if one were to consider governance systems and actors who form other first-tier components of the SESF, social outcomes become equally important drivers of social–ecological outcomes. However, for purposes of clarity in this diagnostic, which unpacks nestedness of RSs, we are excluding other first-tier components of the SESF. Thus, when listing out ASs, even though we use the typology provided by Schlüter et al. (2019a; b), we focus on SEASs as occurring within our NRS and its subsidiary RS. Our diagnostic tool (see Fig. 2a–c) is built keeping in mind the fact that multiple activities can contribute to one AS. For a step-by-step direction on how the diagnostic process may be applied to individual cases, please see Appendix 1.

Cases and methods

We next tested the efficacy of our diagnostic process on unpacking SES/NRS and their associated NAAS dynamics across two distinctive and well-studied empirical cases. Our two cases represent distinct kinds of NRS: on one hand are networks of lakes, representative of traditionally studied common pool resources (other examples include fisheries and irrigation systems). On the other hand, we engage with German winter wheat breeding systems representing non-traditional, technologically mediated SESs (other examples include bioenergy and climate systems). Breeding systems differ from farming systems, as the underlying RU is the flow of genetic differences contained within physical material, like seed or plant parts (Gerullis et al. 2021), thus simultaneously making them divisible packages on a lower level (individual varieties or genes) and continuous streams of material on higher levels (maintained resistance to pathogens over time).

Plant breeding systems therefore show both characteristics of what McGinnis and Ostrom (2014) define as social–ecological technical systems (SETS). First, people dependent upon these systems view services derived from it as continuous streams (unlike traditional SESs where services can be obtained in discrete packets—for example, yields of fish from a lake). In wheat breeding, the benefits are measured through continued selection and propagation of the most suitable varieties for a geographic region. The second distinguishing characteristic of SETS is that there is often clear separation between actors possessing technical expertise to understand construction and maintenance of the system, and those whose sole concern rests with continued access to the resource (McGinnis and Ostrom 2014). In German winter wheat systems, clear separation exists between laboratory and field research stations (providing technical expertise) and commercial wheat farmers (who only depend upon continued access to favourable varieties).

We draw upon our long-term empirical research (see for example Castán Broto et al. 2021; Unnikrishnan et al. 2020; Unnikrishnan and Nagendra 2020; Gerullis et al. 2021) conducted in these contexts. The empirical documentation of NRS landscapes presented in Appendix 2 draws on data obtained through mixed methods approaches. In Bengaluru, these involved transect walks around 24 extinct and extant lakes to document the diversity of tangible and intangible benefits. Discourse analysis of archival documents (from CE 1800 onwards and from various sources: The Karnataka State Archives, The Mythic Society, and the Indian Institute of World Culture in Bengaluru; the National Archives in New Delhi; and the British Library in London) was used to generate historical data on benefits alongside oral history interviews conducted with elderly, long-term residents occupying a radius of 500 m surrounding the field sites. These data were combined with visuals of topographical change tracked through digitising battle plans and toposheets (from 1857, 1935, 1973) and on Google Earth (present day). For the German seed system, we used qualitative interviews, participant observation, and secondary sources from scientific literature or practical guidebooks on breeding, farming, and seed multiplication. Data collection followed a grounded theory style process; interviewees' claims were anonymized, fed into modified questionnaires, and presented to subsequent interviewees for comment. Through this iterative approach, we consolidated individual perspectives into a knowledge consensus of the plant breeding system. To account for survivor bias and sequentiality, these consolidated accounts were presented to the first round of interviewees for validation in a final feedback loop. 18 interviews and 21 participant observations were conducted throughout 2016–2017, and 2019. We used participant observation to supplement our interview data with practical, first-hand experience of processes in breeding programs.

Case applications of diagnostic approach

Before moving on to the case applications of our diagnostic process, it is important to highlight an important consideration here. The delineation of system boundaries as well as the broad SES challenge/s within it relate to the specific research question being addressed. This distinction recognises that a system can be conceptualised in multiple ways and studied through multiple framings; however, it is up to the researcher to choose which framing is most useful for the

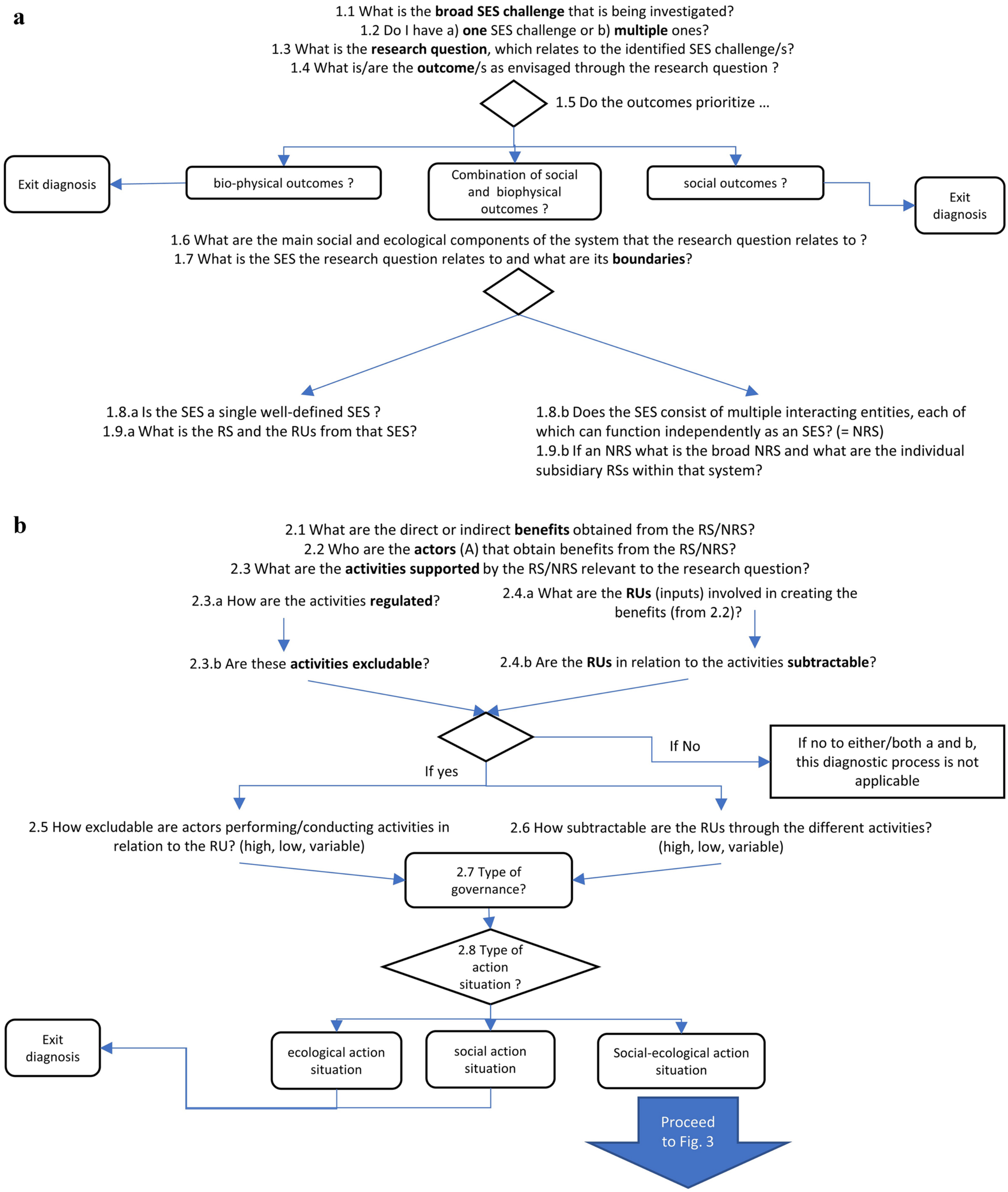

Fig. 2 **a** Diagnostic procedure: Section 1. **b** Diagnostic procedure: Section 2. **c** Diagnostic procedure: Section 3

purposes of answering the research question they originally set out to explore. We now demonstrate the applicability of our diagnostic process, as exemplified by the two case studies.

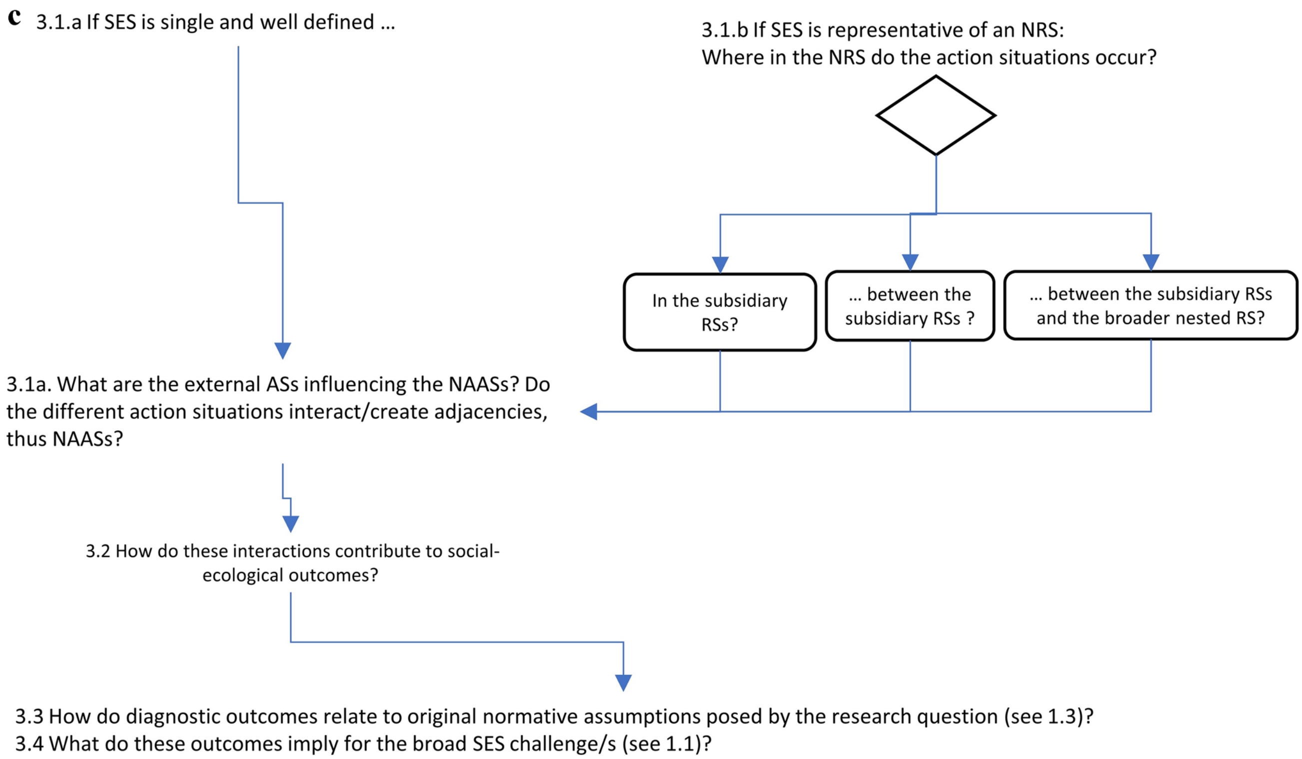

Fig. 2 (continued)

Networks of blue urban commons in Bangalore, India

Understanding drivers of coproduction around urban commons (Q.1.1 of diagnosis as presented in Fig. 2a–c; and Appendix 2) (such as lakes, parks, gardens, etc.) such that they produce ecologically grounded and socially just outcomes has been a long-acknowledged SES challenge. The case of networked lakes in south Indian Bengaluru is a good example of a traditionally studied SES, which easily lends itself to the idea of a NRS. Landlocked, situated in a rain shadow, and devoid of a major water source such as a river, the city has been unusually prosperous since ancient times and has served as a strategic location for colonial establishments (Unnikrishnan et al. 2020). This success of the city is partly attributed to a series of engineered water bodies dating back to about the fourth century CE which provided water to the city. These rain-fed reservoirs (tanks, lakes, or *keres*) were built by tapping into the city's elevation gradient and utilising its naturally undulating terrain. Individual reservoirs were connected by channels, creating an engineered system of flows. Originally constructed to support agrarian communities, these reservoirs over time became integral to the cityscape, providing critical urban ecosystem functions and benefits (Unnikrishnan et al. 2020). This system of engineered water bodies transformed into novel ecosystems (Unnikrishnan and Nagendra 2020), characterised by complex interactions between society and nature, in turn functioning as complex social ecological landscapes.

Urban lake networks provide several shared long-term benefits—these include microclimate regulation, supporting resource dependent livelihoods, acting as biodiversity hotspots, and recharging shallow groundwater reserves. At the same time, given increasing pressures of urbanisation, and the landlocked character of Bengaluru, these reservoir systems have increasingly been viewed as a fluid conduit for the city's sewage—a way to flush out wastewater from the city and into neighbouring regions. Lakes and their channels have also been seen as easily appropriable spaces to convert into other public infrastructure (malls, bus stands, and stadiums). Surviving reservoirs have either lost connectivity in parts of the chain or are treated as standalone water bodies where systemic connections are overlooked. We therefore have multiple social dilemmas arising in this context (Q 1.2). An overarching one relates to the maintenance of connectivity between individual reservoirs of the SES versus conversion of these spaces into other forms of built land use. A similar social dilemma is presented at the level of individual lakes within the network: the maintenance of individual water bodies versus their conversion into built structures or their reimagination as primarily economically driven entities (Unnikrishnan et al. 2016). Individual lakes provide similar and relatively long-term ecosystem services as the larger network—microclimatic regulation, biodiversity, support for resource-based livelihoods, and serving as a local water reservoir. At the same time, in the short term, they are attractive prospects either for redevelopment as real estate or to enhance the value of existing real estate by providing aesthetic and recreational services (Unnikrishnan et al. 2016). This latter viewpoint brings with it several social–ecological challenges: converting lakes into built up spaces increases the risk of urban flash flooding, creates social vulnerabilities among resource dependent populations, and reduces diversity of ecosystem services they provide. However, the larger trend in the region seems to be driven towards an aesthetic and recreation dominated urban vision (Unnikrishnan et al. 2016)—a vision that seems to have sustained itself across at least two centuries.

Considering this contextual background, the objective of applying our diagnostic process is to understand what motivates co-production in this network of lakes in Bengaluru? In other words, what drives inherently heterogeneous communities to invest in the resource collectively? Normatively, we seek to understand what factors may influence heterogeneous communities to engage in lake restoration such that one may achieve favourable ecological outcomes (such as improved water quality or biodiversity) alongside socially just ones (such as representation of diverse interests in the resource) (Qs: 1.3–1.5).

As the network of lakes consists of several individual lakes connected through channels, each of which in turn provide various social–ecological benefits, this system is representative of an NRS. The broad NRS is represented by the network of lakes, while individual water bodies within the network form semi-autonomous subsidiary RSs. Each semi-autonomous subsidiary RS can act as an RU within the NRS but is equally capable of providing RUs (such as fish, water, etc.) by themselves (Qs 1.6–1.9). Actors within this NRS are represented by internally and externally heterogeneous groups of people drawing tangible and intangible benefits—ecosystem services (MEA 2005)—from the resource. Provisioning ecosystem services (material and quantifiable benefits obtained from the system) take the form of entities such as water for commercial and subsistence uses, fish, urban forage, etc. The diversity of intangible benefits such as support for spiritual beliefs, community building, recreation, and aesthetics, are cultural ecosystem services obtained here. Of benefit to the general population and subsequent generations living around the lakes are various regulating services such as pollination, and microclimatic regulation, along with supporting ecosystem services such as nutrient recycling and biodiversity maintenance.

Farmers, fisherfolk, recreationalists, urban foragers, nodal agencies and various other actor groups undertake different activities in and around the NRS. Several actor groups draw benefits from the NRS, through varied activities that are regulated in multiple ways (see Appendix 2 for detailed listing of actor groups and institutional arrangements). The number of actors undertaking these activities as well as ways in which these activities are regulated have implications for the subtractability of stocks of RUs (stock of fish or number of entire lakes), in relation to the activity (fishing or draining entire lakes for building), as well as how easily excludable other actors are from conducting the same activity. These may influence the availability of various ecosystem services (Qs 2.1–2.7).

Figure 3 exemplarily illustrates various activities that give rise to ASs, which occur at multiple levels of the network. Some ASs occur only at the level of the individual lake, whereas others, while taking place at individual lakes, can be influenced by activities occurring elsewhere across the network. For example, the AS characterised by occupying spaces around lake banks and associated fishing activity takes place at the level of individual lakes within the NRS. At the same time, fishing is dependent upon proper functioning of systemic connections across the network. The availability of fish within individual lakes, as well as the quality of water supporting those fish, are both characteristics of the SES that are dependent upon RU flows across the network. Thus, this AS, while occurring at the level of an individual lake, remains deeply embedded within system dynamics of the larger network that it belongs to. This is different from the AS involving appropriation of pasturage from banks of lakes to support livestock grazers, which necessarily occurs only at the level of individual lakes—its functioning remains relatively independent of activities occurring within the broader network (Q: 2.8).

These ASs do not exist independently of each other however, and there are several adjacencies which are created. For example, ASs involving privileged gated communities who appropriate land around individual lakes for real estate, almost always are linked to ASs involving local nodal agencies who are responsible for maintenance and governance of the entire network of lakes. Similarly, ASs involving the appropriation of land and water in and around an individual lake (which are themselves influenced by the larger network that they are part of) are linked to those involving appropriation of pasturage from around individual lakes, largely due to the association between agricultural practices and livestock rearing in the region. What this means is that adjacencies are not created simply between two ASs, but that they can occur along different spatial levels within the NRS. Each of these interactions further link themselves to social–ecological outcomes—in this case with its explicit focus on motivations for co-production, we define these outcomes by the ecosystem services that are enabled or disabled within the system (Qs: 3.1–3.2).

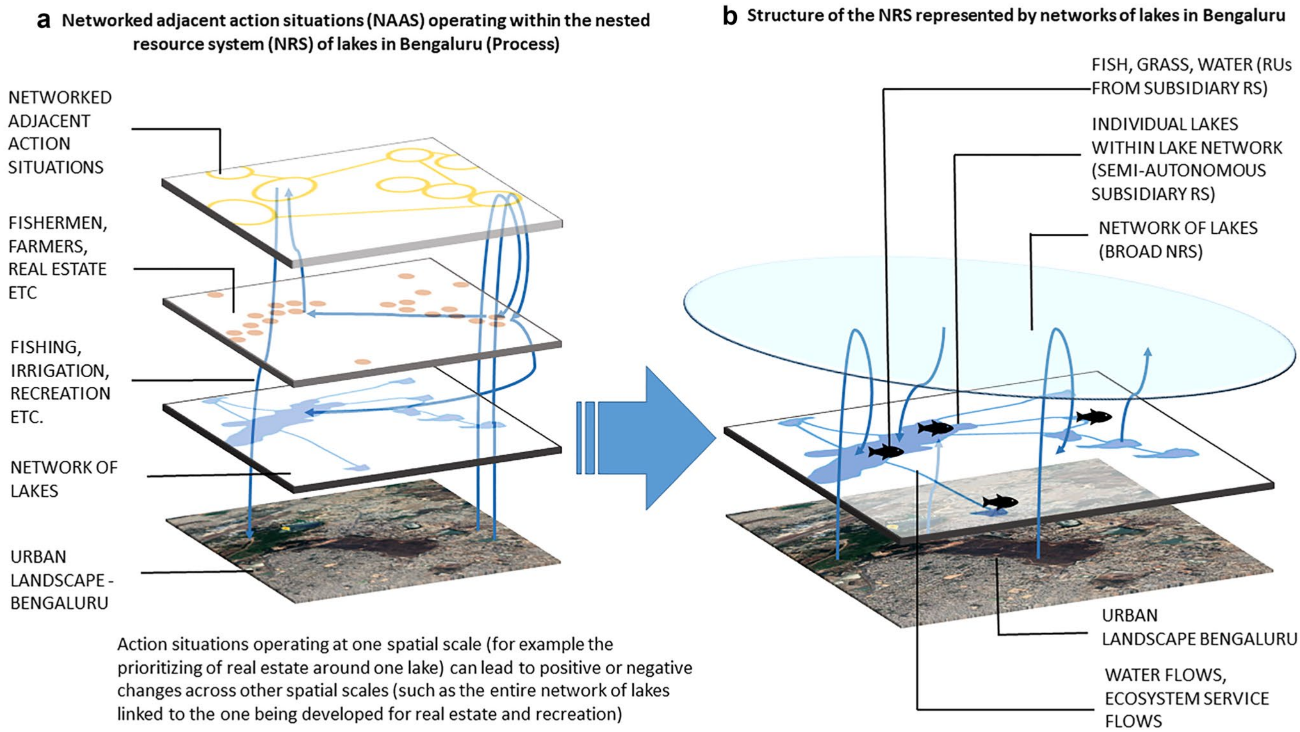

Fig. 3 Exemplary illustration of the network of urban lakes as an NRS with NAASs operating within

In applying our diagnostic process to this case (Appendix 2), we find that only four user groups (nodal agencies, gated communities, private institutions, and urban recreationalists) possess all the following attributes: (a) access, appropriation, management and/or exclusion rights; (b) despite being affected by the larger lake network, tend to operate at the level of individual lakes; (c) access to stakeholder collaboration and information flow; and (d) the ability to directly influence form and function of the ecosystem, while accessing only cultural ecosystem services. This means that power to influence the SES is monopolised by these groups of actors, providing them with greater incentive to engage in co-production efforts towards the resource. Ecologically, this means that efforts are not systemic but targeted only to individual lakes, meaning that the entire NRS is not sustainably rejuvenated.

There are other actor groups who only have access and appropriation rights, are more diverse, depend mostly on provisioning ecosystem services, and who in some cases draw meaning from the systemic nature of the resource. However, these groups usually do not influence the condition of the resource and are not involved in decision-making processes around it. Hence, there is very low incentive for these actors to come together and engage in co-production efforts. This implies that in this case, the success of coproduction around blue commons seems intimately linked to how inclusive the process is to diverse stakeholders of the NRS (Qs: 3.3–3.5).

German winter wheat breeding systems

We utilise our diagnostic process to answer what governance challenges arise in appropriating and provisioning ASs for crop genetic diversity in German winter wheat breeding systems. Relevant for answering this research question therefore is a combination of social and biophysical outcomes. We need to know whether (a) breeders are creating varieties maintaining their long-term genetic pool; (b) subcontracting and selling varieties such that farmer's needs and preferences are being met; (c) farmers are choosing varieties according to their own ecological niches and preferences, such that negative ecological and societal impacts are minimised (Qs:1.1–1.3).

Plant breeding systems ("breeding systems" subsequently) are good examples of SETS involved in creating, maintaining and improving seeds of different crop varieties for farmers to produce food and fibre for human use. Aside from the usual resources used in farming like land, water, fertiliser, and chemicals, breeding systems depend upon genetic variation contained in different plant materials used for breeding. These are very diverse and range across physical material from single allelic snippets, seed, other plant parts, and single plants to variant plots and fields. For actors involved in breeding activities (breeders, plant scientists) these physical flows coincide with information for observing genetic differences in these materials—called traits. As one can tell from this inherent nestedness, these are also NRS. Plant breeding systems as nested, multilevel systems supply and provide affordance for different flows of genetic material in any form and its corresponding information.

We refer to the overall stock of these traits as "genetic diversity" in the following. For actors in seed multiplication, retailing and farming, relevant information results from differences in bundles of traits, called varieties. We refer to the overall stock of these trait bundles as "varietal diversity" in the following (Qs: 1.4–1.5).

The diversity of actors here includes scientists working in crop science or pre-breeding, breeders/breeding firms, seed multipliers, different governmental and non-governmental organisations, and farmers, who plant the varieties and provide their harvest to the system for processing food and fibre. Breeding systems are nested in their underlying genetic set-up along pedo-climatic zones, for which pre-breeding and breeding actors develop varieties (Q: 1.6).

There are economic benefits, mainly income, created for all actors along the seed supply chain: income is generated from variety licensing and subcontracting, selling seed and sales of other inputs accompanying seed (crop protecting agents, fertiliser, machinery). Farmers sell their yield and as such security from stable yields over the years is also a direct economic benefit. Other benefits generated by the system are the future value of a genetically diverse system, and may entail ecosystem services touched by agriculture, like nutrient cycling, groundwater quality, pollination and biodiversity maintenance. The benefits are created from multiple levels within the NRS. While scientists are changing the RUs on a molecular level, applied breeders are interested in changing whole plants, farmers sow seed on the level of their farm plots, retailers push for sales across regions, and governance organisations care about the multiplication areas in regions and states (Qs: 1.7–1.9).

A social dilemma in the appropriation of genetic diversity occurs when breeders reduce the genetic variation in their used material to the point where their gene pool does not contain certain needed traits to maintain cultivar yields anymore, e.g. resistance against a fungus. This may occur when breeders focus their breeding practice on mainly "low hanging fruit" such as qualitative resistance traits. As qualitative traits are determined by only a few allele sequences in the DNA, there is less delay in progress when establishing a new trait into a new variety candidate. Modern molecular marker technologies will allow breeders to find these at a low cost once they are identified. Thereby they can be easily combined into new varieties. Focusing on qualitative traits, nonetheless, comes at the expense of more complicated traits, as there is a trade-off between different breeding goals. If breeders decide to put more resources towards breeding resistance traits they cannot pursue other goals with equal power, as breeders are restricted in their nursery space, person-power, and nursery locations within different environments. A reduction in complex resistance traits would reduce genetic diversity negatively across all breeders. Maintaining genetic diversity of all kinds of traits, however, is vital for sustaining breeding activities and agricultural systems in the long term.

A social dilemma in the appropriation of varietal diversity emerges on a higher level. When too many farmers plant only one variety over large areas, new strains of pests can evolve thereof. One example of this is the occurrence of European yellow rust epidemics in winter wheat of recent decades (Bayles et al. 2000), where strains of plant pathogens evolved from overuse of susceptible varieties. To counteract pests, farmers spray pesticides to prevent the risk of yield losses. Yet, farmers end up spraying more pesticides than necessary (Dachbrodt-Saaydeh et al. 2018), leading to unwanted externalities in their natural environment (Qs: 3.5–3.6).

There is a social dilemma that emerges overarching the two social dilemmas described above. If farmers revert to over-spraying for risk-reduction every year, they need not rely on choosing varieties with well-working resistance but will choose susceptible high yielding varieties (Dachbrodt-Saaydeh et al. 2018). This decreases the market share in varieties with well-working quantitative resistance traits and leads to an added disincentive for breeders to invest in costly generation of these traits (Qs: 3.5–3.6).

The objective of applying the diagnostic process is to understand how to maintain varietal and genetic diversity considering these perverse effects. For German winter wheat cropping, part of these effects is intercepted by governmental regulation and public information diffusion. This is enabled through extension services and public–private breeding efforts. For example, through pre-breeding programs, or encouraging social norms amongst breeders, in ways that reward breeders with the prestige of creating varieties containing complex traits. We are interested in how governing material and information flows on the different levels of the NRS bring about different outcome patterns in genetic and varietal diversity.

Breeders, seed multipliers, retailers and farmers undertake various activities (see Appendix 2, Sect. 2; Qs: 2.2–3.1), which change the shape and size of underlying resource stock of genetic diversity, where each activity is bound by different institutional arrangements, yielding a multitude of NAASs. For example, breeders' activities will influence the stock of RUs of in-nursery genetic diversity and devise the available varieties for other actors. Institutional responses in collective norms on material exchange, state regulations on variety approval and open access to approved varieties influence how the social dilemmas are met. Excludability of actors from various activities is easy, difficult or in some cases varies by individual, as some enabling preconditions determine whether one can undertake the activity. Likewise, subtractability of the resource stock through activities may vary by individual actor or depend on heterogeneous spatial circumstances—for example, subcontracting of varieties for different regions depends on the ecological niches covered.

The earned and expected income gain incentivizes different actors to undertake the activities. Information flows on different agronomic performances of individual biological material (genetic snippets, lines, varieties) direct concrete genetic material to their purpose and spatial positions within the system, leading to different ecological performance measures. Figure 4 exemplarily shows that ASs are networked in two ways: first, through the nestedness of the RSs, where changes on one level of the RS entail changes in the RS on a higher level influencing patterns in ASs on that level. For example, a change on the molecular level of genetic traits about a resistance trait in a variety may impede pest outbreaks in fields of farmers. Second, through transactions taking place between different actors in the respective ASs, where breeders exchange breeding material containing resistance traits and produce varieties which are resistant to certain pests. Multipliers subcontract these varieties if they perform well and sell them through retailers to farmers. Farmers will only spray less if their varieties are resistant to all diseases relevant to their farm. These relationships are dynamic. The ecological world constantly evolves, where pests evolve resistance to formerly tolerant varieties, and plant research is racing to keep up with natural selection. Likewise, social mechanisms of market transactions, subcontracting and collective action change as wider economic and political settings change over time and exert comparable social selection pressures (Qs: 2.2–3.2).

Three individual social dilemmas in networked ASs need to be overcome to not encounter negative environmental impacts on the overall system level: breeders need to invest collectively in quantitative resistance traits to have these in their varieties. Multipliers need to be willing to subcontract these resistant varieties and forego income from accompanying plant protection agents, so that farmers may sow varieties with stable resistances against pests and spray less crop protection agents. In all three of these ASs, the incentives each actor group is faced with point in different directions (Qs: 3.4–3.6).

Discussion and conclusions

In this paper, we engaged with two broad challenges of the SESF. First, we build upon the gap first articulated by Cox (2014) on insufficient decomposition of RS and RU. We attempt to formalise this within the structure of an SES

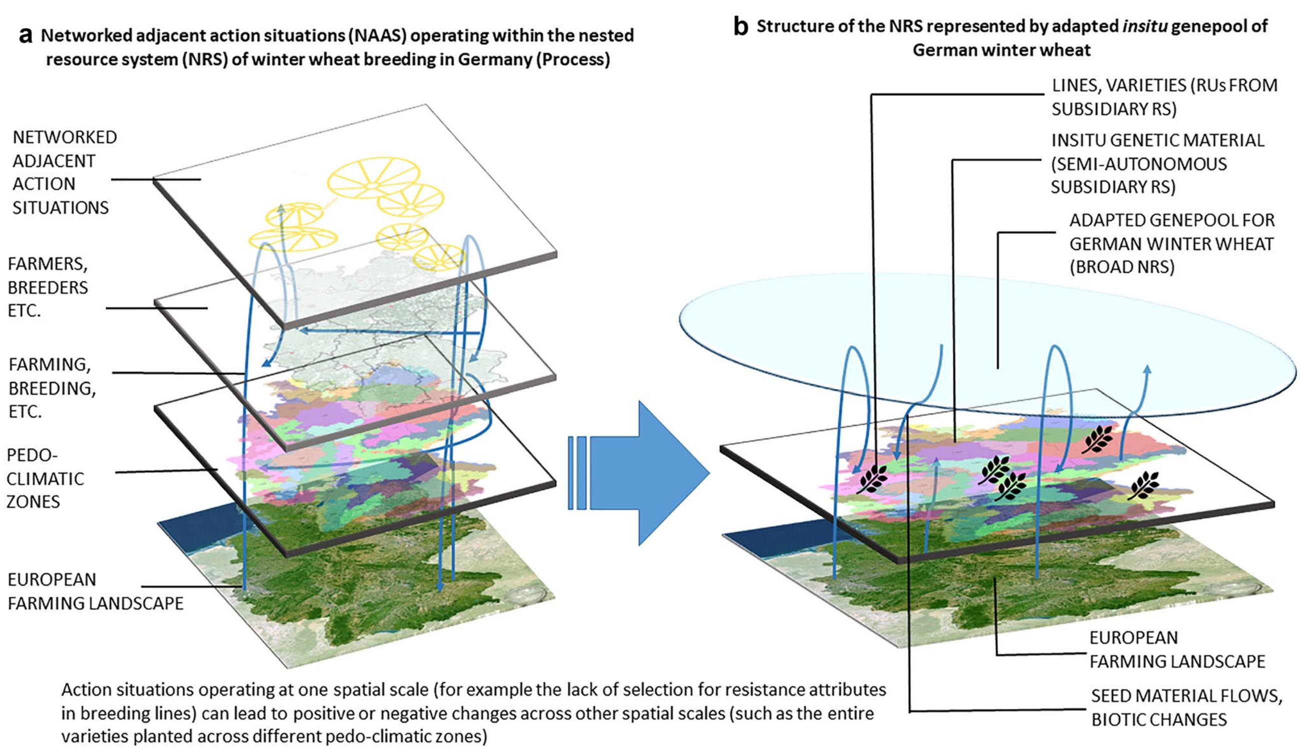

Fig. 4 Exemplary illustration of the German winter wheat breeding system as a NRS with NAASs operating within

by introducing the NRS—the idea that an RS can function simultaneously as both RS and RU depending upon framing of the problem at hand and the boundaries of the system that emerge because of that particular problem frame. We show how NRS contribute to NAASs as nestedness of the NRS leads to a biophysical connection between different ASs (Schlüter et al. 2019). Depending upon one's inquiry, our diagnosis makes physical connections between different ASs visible, providing an opportunity to show these connections spatially, and thus making NAASs spatially explicit (Möck et al. 2019). Second, we propose a diagnostic tool to aid analysts in applying the SESF and articulating associated NAASs to their cases in a standardised manner, allowing for greater comparability across diverse cases (Kimmich et al. 2022). We thus take a step forward in the direction of addressing the acknowledged gap of establishing a protocol for NAAS research (Kimmich et al. 2022; Müller et al. 2013) We have tested the diagnostic process within the context of two distinct systems—a SES characterised by urban lake networks in Bengaluru and a SETS represented by German winter wheat breeding systems. We believe that this diagnostic process may be used successfully in unravelling complexities of other kinds of SESs such as knowledge commons or what are called "new commons". In this section of the paper, we reflect upon the utility of these approaches in expanding our understanding of the SESF and its application to understanding environmental governance challenges.

Decoupling RSs and RUs brings distinct methodological advantages when applying the SESF to cases. First, it allows us to engage with complex dynamics of mid–large-scale systems where there is significant diversity of simultaneously occurring activities operating at multiple spatial levels. Second, it allows us to engage with fluidity of boundaries existing between RS and RU components, while understanding that identities of the RS and RU are largely dependent upon specific activities as opposed to being defined as fixed systemic characteristics (Hinkel et al. 2015). Third, given that RS and RU form the starting point for defining focal ASs, this decoupling allows us to incorporate consideration of simultaneity of interconnected ASs occurring across multiple spatial levels and leading to cumulative outcomes on the SES, which makes it representative of NAASs. It, therefore, provides a first step towards unpacking substitution effects and redundancies that emerge from the complex interplay between actors, their activities, and regulation of those activities.

The application of our diagnostic tool, following the deconstruction of RS and RU allows the analyst to unpack the SES in a standardised manner. This allows for comparisons across diverse cases through meta-analysis—the systematic and consistent coding of cases using the SESF, following which the analyst can observe for patterns of similarities and differences across cases (Ostrom and Cox 2010). These comparisons also provide useful data points for large N-case studies of NAASs and, therefore, serve as a base to aid the generation of middle range theories.

The two cases we analyse using this diagnostic tool help us outline some of these similarities and differences. Both cases are diverse in that they are representative of two distinct systems—an SES and SETS, that are difficult to compare across the geographies in which they occur. At the same time, in decomposing RS and RU components of these systems and applying the diagnostic process, several commonalities come to fore. First, there exist physical connections between RUs in the different ASs of each system—for example, the channels which connect individual lakes within the NRS (enabling flows of water) are comparable to the flows of genetic material enabled in the form of seeds. Second, both systems have multiple social dilemmas occurring at different scales—some of these form overarching dilemmas, while others restrict themselves to the subsidiary RSs in these systems. A complication that emerges from the presence of these multiple dilemmas is that overarching social dilemmas cannot be addressed without engaging with those that occur at lower scales of influence. This is further complicated by inherent heterogeneities emerging between actors, activities, and ASs at multiple levels of the NRS. Third, diagnosis brings out commonalities in the kinds of substitution effects emerging with respect to activities occurring within the NRS through a consideration of simultaneously occurring ASs. For example, the substitution of provisioning food activities in the lake NRS with increased aesthetic and recreational ones would mean that certain user groups are almost immediately excluded from decision-making involving the NRS. Fourth, both systems show redundancies in that multiple actor groups can perform the same activity, or that multiple identities are assumed by the same actor group, therefore with potential to influence the rules-in-use governing these systems. The presence of redundancies means that you can either be an all-in-one entity internalising harmful effects, or you have multiple redundant groups (for example, the farmer/livestock owner) with different abilities to negotiate harmful effects. In the latter case, negative effects are likely to be experienced by those excluded from decision-making either through negotiation or imposition by other groups, as has been demonstrated in both cases we analyse.

From a managerial perspective, these commonalities provide insight into critical points of intervention needed in NAASs occurring within NRS. From the perspective of lake networks, the analysis highlights the need to include information flows across all actor groups, especially those who engage with both systemic and individual levels of the NRS. For example, nodal agencies and real estate groups engage in decision-making around converting lakes, which influences the entire system, yet they do not include fishermen and farmers, who are affected by these decisions. A potential goal, therefore, is to reach stewardship for the lakes' condition across all actor groups, as each individual group can through overuse, hamper social–ecological outcomes of the NRS. From the perspective of plant breeding systems, an important governance challenge involves public agents providing information of variety trials within and across actor groups depending on the level of the RS at which actors operate. For example, maintaining genetic diversity amongst breeders depends on common use and exchange of breeding material, in lengthy processes over several years, which obfuscate causal links between management decisions and breeding outcomes. Distributing information amongst breeders from trials preempts this process and minimises opportunities of defecting amongst breeders, while incentivizing individual improvements of the genetic pool. Yet, economic considerations of ASs later in the seed supply chain (NAASs), influence which material breeders use. Hence, a potential goal for plant breeding systems governance is that variety trials give information such that decision-making by breeders and farmers enables a choice of more sustainable strategies for choosing varieties and breeding material.

These insights on systems could have been generated by other means and using other frameworks. Using the proposed diagnosis, however, will nudge the researcher to explicitly illustrate (a) how the nestedness of an RS does influence decision-making of the actors (incentive structure), (b) how biophysical configurations and information flows arising thereof diverge or overlap for different actor groups. Explicitly showing connections or disconnects between configurations of RS and incentive structures can aid in development of context specific, feasible solutions.

There are some caveats to using this diagnostic process. Applying it to a case requires that the analyst already possesses embedded knowledge of the system. Our diagnostic process also does not intend to prescribe normative views of interactions and outcomes; rather it encourages the analyst to make their own normative assumptions explicit in the process of applying the SESF to a particular case through critical reflection. Our conceptualization of the NRS and its subsequent application in the diagnostic process restricts itself to RS and RU components of the SESF. Engagement with how NRS and NAASs interact across diverse GSs would be a very useful next step along with engaging explicitly with second-tier variables of the SESF. Similarly, advancing diagnostic tools to enable dynamic comparisons across temporally situated NRS and NAASs could enable better comparisons, aiding development of middle range theories drawing on institutional emergence. However, one should note that while this paper adds structure to complexity for individual cases, there is a trade-off between fleshing out detailed items within our diagnostic approach and linking this to data entry and meta-analysis. Future research should consider this trade-off alongside applying this diagnostic tool to multiple cases for comparison and meta-analysis, drawing upon the SESF and NAASs.

Appendix 1: Stepwise guide to using our diagnostic process to diagnose SES/NAASs of interest

In this document, we provide the rationale and a detailed explanation towards each step of using our diagnostic process upon the SESs of interest. This guide draws upon the process we have articulated within the main manuscript through Fig. 2a–c. Our diagnostic process is divided into three sections, each aimed at unpacking a specific aspect of the complexity relating to SESs under question. The three sections are as follows:

1. Section 1: Identifying research questions and characterising the system of interest (Fig. 2a in main manuscript)
2. Section 2: Unpacking action situations relevant to the research question (Fig. 2b in main manuscript)
3. Section 3: Delineating NAASs and associated SES outcomes (Fig. 2c in main manuscript)

We now proceed to unpack each of these sections in greater detail.

Section 1: Identifying research questions and characterising the system of interest

For a researcher wishing to understand the complexity of SES they are investigating, it is important to first articulate their research question in relation to the SES of interest. The following questions guide the researcher in this process.

1.1 **What is the broad SES challenge that is being investigated?**

Every piece of research begins with the articulation of a broad challenge that the researcher wishes to investigate. This could be as diverse as an attempt to understand the impacts of climate change upon complex SESs or to understand the dynamics of collective action operating within the context of natural resource governance. Articulating this broad research objective is the starting point of our diagnostic process.

Note: We acknowledge that there may be a wide range of incentive structures within natural resource governance and these can include forms of cooperation, conflict, or indifference (Bruns and Kimmich (2021) characterise incentive structures through a game theoretical approach as win–win, discord, and threat, with exchange, coordination, and independence as their primal archetypes) and it remains up to the researcher to determine the nature of incentive structure associated with the SES challenge they are investigating.

1.2 **Do I have a) one SES challenge or b) multiple ones?**

Starting with the challenge identified in 1.1, consider whether it may be neatly defined with specific and single outcomes, or whether they can be split into multiple related subcomponents.

For example, in researching the impacts of climate change upon an SES, we must consider multiple related elements to the problem such as those related to adaptation, vulnerabilities, technology and infrastructure involved, global politics, etc. On the other hand, if the challenge being investigated relates to institutional arrangements influencing forest cover, we have one clearly defined SES challenge relating to a specific outcome, namely forest cover.

1.3 **What is the research question that relates to the identified SES challenge?**

Moving from the broad challenge into the specifics of the case being investigated, the analyst must now articulate the research question that guides their work. Research questions are specific and explain other elements of the research design including the articulation of outcomes as envisaged through the project (Cox 2015). For example, what are the institutional arrangements sustaining forest cover in tropical deciduous forests of central India?

1.4 **What is/are the outcome/s as envisaged through the research question?**

Drawing on 1.3, the analyst must now reflect upon the kinds of potential outcomes arising from the research question they have articulated. In the example given above, there can be multiple SES outcomes. Certain institutional arrangements can act to sustain forest cover in the forests concerned, while others may act against sustaining it. The normative or desired outcome as envisaged through the research question, however, is that forest cover remains sustained and that it is brought about through a certain configuration of institutional arrangements.

Note: In our opinion, most, if not many analyses have a normative standpoint in mind. We do acknowledge however, that there will always be some that are not normatively motivated.

1.5 **Do the outcomes prioritise a) biophysical outcomes; b) combination of social and biophysical outcomes; or c) social outcomes**

Potential outcomes as envisaged by the researcher are subjective and may relate to their specific positionalities. Accordingly, a researcher might prioritise only a) biophysical outcomes (for example when the desired outcome is defined only by improved ecological parameters such as biodiversity or water quality) or b) a combination of social and biophysical outcomes (for example socially just institutions resulting in improved biodiversity or water quality), or c) only social outcomes (for example if the desired outcome is envisaged as being composed of socially just institutions alone). Our diagnosis concerns itself with b) namely the combination of social and biophysical outcomes, which alone proceed into the next question. If the analyst is looking at either only ecological or only social parameters, they may exit the diagnosis at this stage.

1.6 **What are the main social and ecological components of the system that the research question relates to?**

Following from 1.5, as this diagnostic process relates to social and ecological systems, it follows that the analyst must identify the social and ecological components of their system of interest. For example, in the research question articulated above relating to institutions that sustain forest cover in India, we can identify both social and ecological components that form the system. Social elements involve actor groups and the various institutional arrangements that may be formed by these actor groups. The forest itself and everything it contains within (such as rivers, trees, fauna, etc.) represent the ecological component of the system.

1.7 **What is the SES the research question relates to and what are its boundaries?**

Once we have the social and ecological elements relating to our question and system of interest identified, we now need to define the specific boundaries of the SES based upon our responses to 1.5 and 1.6. In the example above, our SES comprises of tropical deciduous forests in central India and because we are interested in institutional arrangements associated with them, we may delineate our boundaries using jurisdictional markers around the forest. Other ways of defining system boundaries may also exist and delineating these depend strongly upon how the analyst articulates responses from 1.1 to 1.6 and what they are specifically interested in.

1.8a **Is the SES a single well-defined SES? Or b. Does the system consist of multiple interacting entities, each of which can function independently as an SES (= NRS)**

Once the SES has been delineated, the analyst would next need to identify whether the SES as contained within the boundaries they have identified is discrete and well defined (such as a single aquifer) or whether the SES contains multiple nested entities each of which can function independently as an SES on its own, i.e. whether the SES is in fact an NRS. In the example, we have been working with, a forest can be considered an NRS—it can comprise not just of the well-defined tree dominated entity we identify as a forest, but also rivers, lakes, or grasslands within that are equally capable of forming discrete SESs on their own.

1.9a **What is the RS and RU within that system or b. If system is an NRS, what is the broad NRS and what are the individual subsidiary RSs in that system?**

If the SES is discrete and well defined, it follows that we can delineate specific Resource Systems (RS) and Resource Units (RU) from it. For example, if we were considering a single aquifer as our RS, it stands to follow that the groundwater obtained from it would be our RU. On the other hand, if the SES is characteristic of an NRS, then it is next time to delineate what the broad NRS is and what individual subsidiary RSs exist nested within it. In the example of forests that we have been using, our broad NRS is represented by the tropical deciduous forest—our system of interest. Entities within it such as rivers or grasslands, may be considered subsidiary RSs as each of them can produce discrete RUs on their own (for example water from a river flowing within that forest).

Section 2: Unpacking action situations relevant to the research question (the following questions in the diagnostic protocol are relevant to both SES and NRS cases)

2.1 **What are the direct and indirect benefits obtained from the RS/NRS?**

Once the analyst determines whether the system, they are engaging with is an RS or an NRS, they will need to identify the direct and indirect benefits that are obtained from the system of interest, that are relevant to the research question. Direct benefits from our example above may be provisioning benefits (such as measurable and quantifiable benefits like timber, non-timber forest products, etc.), while indirect benefits can include cultural benefits (like spiritual practices), regulating benefits (microclimate regulation), or supporting benefits (such as nutrient cycling). We suggest the terminology adopted by the Millennium Ecosystem Assessment (MEA 2005) to characterise ecosystem services into provisioning, regulating, supporting, and cultural services, is particularly valuable in this context. It is also important to note that the RS/NRS may provide multiple benefits that need to be considered in relation to the research question being investigated.

2.2 **Who are the actors (A) that obtain benefits from the RS/NRS?**

Benefits are usually accrued by actors who engage directly or indirectly with landscapes represented by the RS/NRS. Therefore, for each benefit identified, the analyst must identify the actors who are involved. For example, timber from a forest may be obtained for fuel/subsistence/commercial purposes by local communities living near it, or by loggers representing the interests of large companies wishing to benefit from the resource.

2.3 **What are the activities supported by the RS/NRS relevant to the research question?**

Relating to these benefits and closely linked to the idea advanced by Hinkel et al. (2015) that subtractability and excludability within a CPR problem are linked directly to activities supported by the system (and are not intrinsic properties of the system by themselves), the analyst must now identify the various activities supported by the RS/NRS. An example of activities occurring in our exemplary forest would be logging, farming, harvesting non-timber forest products, fishing, etc.

2.3a **How are the activities regulated?**

Each activity undertaken is likely to be regulated in some manner and identifying and articulating these regulations forms the next step of our diagnostic process. For example, fishing from the river in our forest can be commercial or subsistence based. It may be that in the system of interest, commercial fishing is regulated through a structured tender-based process, while subsistence fishing is unregulated, making them two distinct activities occurring within our RS/NRS.

2.3b **Are these activities excludable?**

In the next step of the diagnostic process the analyst should examine whether the activities they have described are excludable—is it possible to exclude actors from participating in the activity? In the example given in 2.3a, tender-based commercial fishing by virtue of its own characteristics can exclude actors who do not participate in the tendering process, while on the other hand, it is difficult to exclude actors from the more unregulated subsistence-based fishing activity.

2.4a **What are the RUs involved in creating the benefits (from 2.2)**

Benefits from an RS/NRS are always linked to RUs obtained from it. Therefore, in this next step to our diagnostic process, it is important to characterise the RUs involved in creating the benefits. For example, provisioning benefits may be linked to specific RUs such as water or fish from a river, or timber from the forest.

2.4b **Are the RUs in relation to the activities subtractable? (if no to 2.3 or 2.4 a or b, exit)**

We know from Hinkel et al. (2015) that activities conducted around a system are important towards understanding whether RUs are subtractable or excludable. Subtractability refers to the idea that the amount of RU available to subsequent users may diminish each time it is extracted from within the RS/NRS. For example, if our activity relates to harvesting the non-timber forest product of wild honey, the associated RU would be the limited number of beehives in the forest. The total number of beehives available to harvesters will decrease each time honey is extracted from one of them. Analysts using our diagnostic process must now reflect upon whether the RUs extracted in relation to various activities occurring within their system are similarly subtractable or not.

If the analyst determines that the RUs are neither excludable nor subtractable in relation to the activities being examined within their system of interest, the remainder of this diagnostic process is not applicable to the case in question as this diagnostic procedure relates specifically to CPR problems.

2.5 **How excludable are actors performing/conducting activities in relation to the RU (high, low, variable)**

Once the analyst determines that the RUs are in fact excludable in relation to the activity being performed, they may now proceed towards analysing the gradient of exclusion involved as being high, low or variable. For example, if we consider two activities from our example namely commercial tender-based fishing and subsistence fishing, excludability is high in the former, and low in the latter. On the other hand, if an activity within the system is regulated by means of collectively designed institutions (for example spiritual beliefs around a system), the extent of exclusion may become unclear. It may be that the activity is open to everyone except specific members of the community as designated by the rules governing the activity. This would mean that exclusion is high with respect to the members of the community being actively excluded from the activity, but low with respect to everyone else. In cases such as these, we propose that the analyst assumes excludability as being variable.

2.6 **How subtractable are the RUs through different activities (high, low, variable)?**

Just as with exclusion, the subtractability of an RU is also activity dependent. We propose that an analyst identifies whether the degree of subtractability of RU in relation to activities is high, low, or variable. For example, the subtractability of fish as an RU is highly variable dependent upon the nature of activity involved. It can be high if fishing is conducted as a commercial activity or low if it is a case of subsistence fishing by local forest dependent communities. Seasonal changes to fish populations can also affect the relative subtractability of fish populations. This is quite different from say an activity such as collecting wild honey, where the subtractability of beehives within the forest is clearly very high.

2.7 **Type of governance**

The next step within our diagnostic process is to articulate the kind of governance regime operating across each activity within the system of interest. This is important because while the RS/NRS as a whole may be governed through one form of governance (such as a centralized state-based mechanism), specific activities within it may be governed differently. For example, while the forest in question may be subject to state led regulations, access to spiritual benefits from specific regions of that forest may be subject to collective ones, that may or may not intersect with that governing the broader forest.

2.8 **Type of action situation—ecological AS, social AS, or social ecological AS. (Only SEAS proceeds to next)**

Once activities and their various associations have been delineated, the analyst would need to identify the nature of action situation (AS) involved around these activities. ASs may be of different kinds, namely social AS, ecological AS, or social–ecological ASs (SEAS). Given that we are explicitly interested in coupled social ecological outcomes, it is important at this stage to only list SEAS. As Schluter et al. (2019a; b) define it, SEAS involve interactions between human actors, ecological entities, their capacities, as well as the institutional arrangements that govern this complex of interactions. These SEAS can be of two kinds—provisioning AS or appropriation AS. The analyst now identifies which activity may be designated a provisioning AS and which may be exemplary of an appropriation AS. For example, the drawing of water from a river to meet irrigational purposes is an example of an appropriationAS, while the ASassociated with governing and providing recreational spaces within the forest may be examples of provisioning ASs.

Section 3: Delineating NAASs and associated SES outcomes

3.1a **If system is single and well defined, how many ASs are there? Do the different ASs interact or create adjacencies, thus NAASs?**

If (through 1.8a), the analyst has identified that they have a single and well-defined SES, it is now time to recognise the number of ASs of relevance to the research question being investigated. Further, what are the different interactions that occur between these ASs? Do the outcomes of one AS influence another AS thereby creating adjacencies and therefore NAASs? Going back to our example of the forest, ASs guiding activities such as hunting and poaching can potentially influence ASs involving the creation of rules governing the entire forest, and therefore exert influence on social ecological outcomes.

3.1b **If SES is representative of an NRS, where in the NRS do the ASs occur? In the subsidiary RSs? Between the subsidiary RS? Between the subsidiary RS and the broader NRS? (Then link to questions in 3.1a)**

If (through 1.8a), the analyst has determined that they are in fact working with an NRS, then the next step would be to identify where in the NRS do specific ASs occur. Do they occur within the subsidiary RS (for example, fishing in a river flowing within the forest), or between subsidiary RSs (for example, livestock grazing on the fertile banks of the river flowing within the forest), or between the subsidiary RS and the broader NRS (for example, ASs involving the use of fertile soil within the forest that has been irrigated by water from the river flowing within the forest)? Once this spatiality has been determined, the analyst next proceeds to the questions identified in 3.1a to identify the various NAASs operating within the NRS across these spatial differences.

3.2 **What are the external ASs influencing the NAASs?**

At this stage of the diagnostic process, the analyst must now ask what external ASs influence the NAASs that have thus far been delineated. These external ASs could take the form of ASs relating to other CPR arrangements influencing the system and question of interest, those relating to broader social–ecological contexts (for example, the influence of external ecosystems or socio-political arrangements that influence the system of interest).

3.3 **How do these interactions contribute to social–ecological outcomes?**

Once NAASs and factors influencing these NAASs have been identified, the analyst must now reflect upon the complex of interactions that have been teased out through this process and the kinds of social–ecological outcomes that emerge. Depending upon whether the system under consideration is representative of an SES/NRS, these outcomes can either relate to the SES as a whole or to the broad NRS or individual subsidiary RSs. It is important to note that there may be multiple outcomes relating to each AS/NAAS occurring within the system. An example of a social–ecological outcome in our exemplary forest would be an effort to sustain the forest through stringent centralized governance regimes in response to poaching alongside more collectively managed institutional arrangements relating to access and appropriation of non-timber forest products.

3.4 **How do diagnostic outcomes relate to the original normative assumptions posed by the research question (see 1.3)?**

The final two questions of our diagnostic exercise relate to linking our case study to the original motivations behind doing the exercise. In this penultimate step of the procedure, we ask the analyst to reflect upon how social–ecological outcomes, as unpacked through this stepwise decomposition of the SES/NRS relate to the original assumptions posed by the research question (from 1.3). Further, if the case relates to an NRS, does unpacking NAASs across the various spatial elements of the NRS provide additional nuance towards understanding the case being investigated?

3.5 **What do these outcomes imply for the broad SES challenge/s (see 1.1)?**

In the last step of our diagnostic process, we ask the analyst to reflect upon how these outcomes (as unpacked through our diagnostic tool) have implications for the broad SES challenge/s identified through 1.1.

Appendix 2: Diagnostic characteristics of the two cases—networked lakes in India and German winter wheat breeding systems

Section 1: Identifying research questions and characterising the system of interest

Q No.	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
1.1	What is the broad SES challenge that is being investigated?	Drivers of coproduction in urban water commons	Provisioning and appropriation of genetic diversity: in situ and ex situ
1.2	Do I have a) one SES challenge or b) Multiple ones	Multiple challenges relating to social and ecologically just forms of coproduction	Multiple social dilemmas: providing genetic diversity along a supply chain of scientists, breeders, seed multipliers and farmers
1.3	What is the research question that relates to the identified SES challenge/s	What drives inherently heterogeneous communities to come together and invest in the resource collectively? What motivates co-production in the networked lake system of Bengaluru?	What governance challenges arise from provisioning genetic diversity?
1.4	What is/are the outcomes as envisaged through the research question?	To understand the factors that could potentially enable heterogeneous actor groups to successfully engage in coproduction of lakes within the networked lake system	To understand what type of coordination mechanisms are used to channel seed material and corresponding information on agronomic performances and material quality
1.5	What nature of outcomes are being prioritised?	Combination of social and biophysical outcomes Here the social–ecological outcomes envisaged would be heterogeneous actors successfully coming together towards an inclusive co-production effort that result in sustainable rejuvenation of individual lakes as well as the entire system that they are a part of	Combination of social and biophysical outcomes **Social–ecological outcomes**: Breeders creating varieties maintaining their long-term genetic pool; Subcontracting and selling varieties, such that farmers' needs and preferences are being met and manifest in ecological outcomes of varietal diversity; Choosing varieties according to their own preferences and societal considerations by the farmer
1.6	What are the main social and ecological components of the system that the research question relates to?	**Social components:** Resource user groups (Farmers, fishermen, recreationalists, urban foragers, etc.), Institutional arrangements (civil society, RWAs, local bureaucracies, rules, norms, etc.), property rights regimes, Socio-cultural diversity and traditions (Heterogeneities among actors, cultural and religious beliefs or practices associated with the lake) **Ecological components:** the lakes (quality), water, fish, biodiversity (both flora and fauna), soil and silt, supporting and regulating ecosystem services (groundwater recharge, local microclimate regulation, maintaining biodiversity)	**Social components**: scientists, breeders, multipliers,agricultural retailers, farmers, institutional arrangements (Lobbying groups, breeders rights, intellectual property rights) **Ecological components**: genes snippets, seed, plants, field variants, fields, genetic diversity; regulating ecosystem services (groundwater quality, soil quality, maintaining biodiversity, agro-climate zones, growing regions)
1.7	What is the SES the research question relates to and what are its boundaries?	SES relates to the entire network of lakes within the city of Bengaluru. This network formed by individual lakes connected to each other via channels, which constitute a single chain enabling unidirectional water flow forms the boundaries of this system	The SES relates to the entire chain and use of genetic material, being used from pre-breeding (research projects bringing in foreign genetic material for localised breeding) to farming
1.8	Is the SES single and well defined or is it an NRS?	The system is representative of an NRS	The system is representative of an NRS

Q No.	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
1.9	What is the broad NRS and what are the individual subsidiary RSs within that system?	Broad NRS = entire network of lakes Subsidiary RS = individual lakes in that network	Broad NRS = entire chain of activities using seed material Subsidiary RS = individual types of material usage in breeding nurseries, seed multiplication and on farm usage as varieties

Section 2: Unpacking action situations relevant to the research question

Q. No.	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
2.1	What are the direct or indirect benefits obtained from the RS/NRS	**Provisioning ecosystem services** (Water for various domestic and commercial activities), Fish, urban forage, pasturage, silt, etc.) **Cultural ecosystem services** (Support for cultural, social, or religious traditions and practices—*ashwathkattes* (raised platforms containing a combination of Neem and Peepal trees *(Azadirachta indica, Ficus religiosa*, respectively), carrying cultural significance to local communities), sacred forests, temples, cemeteries associated with the water bodies) **Regulating ecosystem services** (microclimate regulation, pollination, flood control, etc., groundwater recharge) **Supporting ecosystem services** (Biodiversity maintenance, nutrient recycling, etc.)	**Economic benefits:** income generated from variety licensing and subcontracting, income generated from selling seed, income generated from other inputs accompanying seed (crop protecting agents, fertilizer, machinery), income from selling yields, security from stable yields and incomes; future value of a genetically diverse system **Non-economic benefits**: nutrient cycling, groundwater quality, pollination, biodiversity maintenance

The remaining questions of section 2 and question 3.1 are addressed in the following tables for each case

2.2 Actors	2.3 Activities supported by the system	2.3a Regulation of activity in relation to RU	2.3b Excludability of actors from activity	2.4a Stock of (RU) involved	2.4b Subtractability of RU with respect to activity	2.7 Type of governance	2.8 Action situation	3.1b Where in the NRS do the AS occur
Fishermen	Catching fish	Tender based, Access and appropriation rights	Easy	Fish stock	Variable	Undefined	Appropriating fish and spaces to fish within	Individual lake (fishing activity), influx from lake network
Recreational fishermen	Catching fish Occupying a location for undisturbed fishing	None, Access and appropriation rights	Difficult Difficult	Fish stock All available fishing locations	Low High	Public CPR		Individual lake (fishing activity), influx from lake network)
Farmers	Drawing out water by means of electric pumps from the lake for irrigation	Collective rules Access, appropriation rights	Variable	Water	Variable	Undefined	Appropriating water and other inputs for irrigation	Individual lake, influx from lake network, Network of lakes
	Occupying a location to place electric pumps or other water drawing equipment		Variable	All available locations on bank of lake	High	Undefined		Individual lake
Urban foragers	Collecting green leafy vegetables growing on the banks of the lake	None, Access and appropriation rights	Difficult	Greens	High	CPR	Appropriating urban forage for subsistence	Individual lake
Gated communities	Making use of prime real estate that offers 'lake view' apartments/houses for a premium	Toll, Access, appropriation and management rights	Easy	Land, Water	Low	Toll/Club	Appropriating land around lake for real estate purposes and forming Residents Welfare Associations for management	Individual lake; however, ecological quality of water body affected by that of larger network

2.2 Actors	2.3 Activities supported by the system	2.3a Regulation of activity in relation to RU	2.3b Excludability of actors from activity	2.4a Stock of (RU) involved	2.4b Subtractability of RU with respect to activity	2.7 Type of governance	2.8 Action situation	3.1b Where in the NRS do the AS occur
Nodal agencies	Maintaining water body for public use	State regulated, Access, appropriation, management, and exclusion rights	Difficult	Entire lake	Low	Public	Provisioning water, Managing and regulating most activities associated with lake	Entire network of lakes but individually considered
Private Institutions (such as corporate groups or information technology parks)	Maintaining the water body and drawing recreational benefits for their employees	Private rules Access, appropriation, and management rights	Easy	Entire lake	Low	Toll/Club	Providing aesthetic and recreational spaces through PPP arrangements	Individual lake;, however, quality of the waterbody is affected by the larger network it forms a part of
Livestock owners	Livestock grazing	Open access Access and appropriation rights	Difficult	Grass on bank of lake or shallow waters	High	CPR	Appropriation of grass from lake banks	Individual lake
		State regulated Access and appropriation rights	Easy		High	Private		
		Private rules Access and appropriation rights	Easy		High	Private		
	Livestock washing	Open access Access and appropriation rights	Difficult	Water from the lake	Low	Public	Appropriation of water from lake	Individual lake; influx from lake network
		State regulated Access and appropriation rights	Easy		Low	Toll/Club		
		Private rules Access and appropriation rights	Easy		Low	Toll/Club		
	Providing drinking water for livestock	Open access Access and appropriation rights	Difficult	Water from the lake	Low	Public		Individual lake; influx from lake network
		State regulated Access and appropriation rights	Easy		Low	Toll/Club		
		Private rules Access and appropriation rights	Easy		Low	Toll/Club		

2.2 Actors	2.3 Activities supported by the system	2.3a Regulation of activity in relation to RU	2.3b Excludability of actors from activity	2.4a Stock of (RU) involved	2.4b Subtractability of RU with respect to activity	2.7 Type of governance	2.8 Action situation	3.1b Where in the NRS do the AS occur
Dhobies—commercial washerfolk	Washing clothes on the banks of the lake	Open access Access and appropriation rights	Difficult	Water from the lake	Low	Public	Appropriating water and spaces around the lake for washing	Individual lake; influx from lake network
		State regulated Access and appropriation rights	Easy		Low	Toll/Club		Network of lakes
	Finding appropriate places to set up washing stones and other equipment	Open access Access and appropriation rights	Difficult	All available locations for washing	High	CPR		Individual lake
		Collective choice rules Access and appropriation rights	Variable		High	Undefined		
		State regulated Access and appropriation rights	Easy		High	Private		
Urban recreationalists	Jogging, running, walking, sitting, playing music, swimming, exercising	Open access Access and appropriation, and management rights	Difficult	Water body and its banks	Low	Public	Appropriating the water body and its surroundings for recreation, collaborating for lake maintenance	Individual lake; however, quality of water body is influenced by that of the larger network
		State regulated Access and appropriation, and management rights	Variable		Low	Undefined		
		Private Access and appropriation, and management rights	Easy		Low	Toll/Club		
Urban residents	Performing religious rituals	Open access Access and appropriation rights	Difficult	Water	Low	Public	Appropriating water, space, and mud for spiritual purposes	Individual lake, lake network
			Variable	All available locations for conducting rituals	High	Undefined		Individual lake
			Difficult	Mud/Clay	Low	Public		Individual lake

Case 2: Winter wheat breeding systems of Germany

Actors	Activities supported by the system	Regulation of actors/activity in relation to RU	Excludability of actors from activity	Stock of RU	Subtractability of RU with respect to activity	Types of Goods	Action Situations	Level at which action situation occurs	Social outcomes	Ecological outcomes
Breeders	Pre-breeding	Internationally regulated	Variable	Rest of primary gene pool	Variable	Undefined	Breeders providing genetic diversity and appropriate genetic diversity from different RU Stocks for their breeding activities	Molecular; plant	Access to choosing preferred traits (option value); information flow	Directing gene flows
		State regulated	Easy	Adapted breeding material to temperate German climate	Variable	Undefined		Plant; field		
	Creating/maintaining / improving inhouse variation	State regulated Collective-regulation	Easy	Lines submitted to VCU trials	Low	Toll good		Field	Information flow collaboration between breeders	On nursery genetic diversity
		Open Access	Difficult	All available varieties on DVL	Low	Public good		Field		
		Private rules	Easy	Diversity of genotypes and knowledge about internal lines within individual breeding firm	High	Private good		Molecular, plant, field	breeding activities	
	Selecting from inhouse variation	Private rules/Heuristics	Easy		High	Private good		Molecular, plant, field		

Actors	Activities supported by the system	Regulation of actors/ activity in relation to RU	Excludability of actors from activity	Stock of RU	Subtractability of RU with respect to activity	Types of Goods	Action Situations	Level at which action situation occurs	Social outcomes	Ecological outcomes
	Subcontracting varieties to multipliers/agricultural retailers	State regulated	Variable	Total expenditure of agricultural retailers / multipliers	Variable	Undefined	Provisioning of varieties by retailers	Landscape	income from licencing fees and subcontracting	Varieties being multiplied
Multipliers	Selling certified seed to agricultural retailers	State regulated	Variable	Total expenditure of agricultural retailers	Variable	Undefined		Landscape	income from selling seed	spread of different varieties across different geo graphical regions
	Multiplying seed for breeders	State regulated	Variable	Total expenditure of breeders for licensed activities	Variable	Undefined		Landscape	income from licences	
Agricultural Retailers				Multiplied seed	Low	Undefined		Landscape	income from selling seed	
	Selling certified seed to farmers	State regulated	Easy		Low	Private good	Farmers appropriate seed = they buy or farm-save seed and use them for farming	Landscape	seed becoming accessible to individual farmers	Spreading different varieties in a specific area
				Farmers total expenditure	Low	Private good		Farm	income from selling seed	
	Selling fertilizers and pesticides matching the respective seed	State regulated State regulated	Easy		Variable	Undefined		Farm	income from selling other inputs	
				All available seed	High	Private good		Landscape	saving seed for resowing	
					Low	Undefined		Field		
Farmers	Conventional/organic winter wheat cropping	State regulated	Variable	Other inputs to farming	Variable	Undefined		Field Landscape	Undefined	In situ variation of varieties (e.g. usage of resistant varieties); soil quality, biodiversity, water quality

Section 3: Delineating NAASs and associated SES outcomes

Q. No.	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
3.2	How many ASs are there? Do the different ASs interact/create adjacencies, thus NAASs?	13 ASs may be delineated. Yes, NAASs are created through adjacencies across the various ASs	3 ASs may be delineated. Yes, NAASs are created through adjacencies across the various ASs
3.3	What are the external ASs influencing the NAASs?	This is a community that has historically engaged in coproducing its waterscape, and therefore this can serve as an incentive system (see for instance Unnikrishnan et al. 2020), size of the lakes (smaller lakes have easier boundaries to manage), sewage inflows into individual lakes affecting water quality, city and state level sewage discharge, pollution, and wetland regulation policies (which require greater engagement and strategic negotiation between state bureaucratic structures, and the communities engaged in coproduction)	International policy regulating access and benefit sharing of seed internationally, supra- and -national organisation of variety testing and monitoring
3.4	How do these interactions contribute to social–ecological outcomes?	Only four user groups (nodal agencies, gated communities, private institutions, and urban recreationalists) possess all the following attributes: Access, appropriation, management and/or exclusion rights Their activities define the RS as being public, toll, or undefined goods Despite being affected by larger lake network, tend to operate at the level of individual lakes Access to stakeholder collaboration and information flow Ability to directly influence the form and function of the ecosystem, while accessing only cultural ecosystem services This means that power to influence the social ecological system is monopolised by these groups of actors, allowing them to engage in co-production efforts towards the resource. Ecologically, this means that efforts are not systemic but targeted only to individual lakes, meaning that the entire social ecological system is not sustainably rejuvenated. Other actor groups (who only have access and appropriation rights, are more diverse, who depend mostly on provisioning ecosystem services, and who in some cases draw meaning from the systemic nature of the resource) cannot influence the condition of the resource or be involved in decision-making processes around it	While scientists and breeders mainly contribute to provisioning and appropriating genetic diversity within seed material on a genetic and plant level. Seed multipliers, agricultural retailers, farmers appropriate crop genetic diversity in form of appropriating varieties

Q. No.	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
3.5	How do diagnostic outcomes relate to original normative assumptions posed by the research question (see 1.3)	Given that decision-making powers around the system of lakes rest only with a few groups of actors interacting with the SES, it follows that other actors do not have sufficient incentive to engage in co-production efforts, even though their uses of the resource can range from a public goods dilemma to a CPR situation Further, despite the networked nature of the system, actors with the ability to modify the ecosystem only act at the level of individual lakes, while user groups who explicitly make use of the networked character (such as farmers) are excluded from decision-making action situations. There is a need to consider the systemic character of this lake system, and that can only be done through inclusive decision-making Note: Exceptions to the case exist where management rights are given to each stakeholder involved in the co-production process, but these are too few and far in between	The earned income and expectation of income gain incentivizes the different actors to undertake the activities The information flows on the different agronomic performances of individual biological material (genetic snippets, lines, varieties) direct the concrete genetic material to its purpose and concrete positions within the whole system, leading to the different ecological performance measures Three individual social dilemmas in networked action situations need to be overcome for not encountering negative environmental impacts on the overall system level: Breeders need to invest collectively in quantitative resistance traits to have these in their varieties. Multipliers need to be willing to subcontract these resistant varieties and forego income from accompanying plant protection agents, so that farmers may sow varieties with stable resistances against pests and spray less In all three of these action situations, however, the incentives each actor group is faced with points in different directions
3.6	What do these outcomes imply for the broad SES challenge?	The success of urban coproduction around blue commons seems intimately linked to how inclusive the process is to diverse stakeholders of the resource system	Failure in reducing ecological impacts through spraying can be traced back to the conflicting interests in incentive structures along the seed chain/ resource system

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