CHAPTER FOUR

A metacoupling lens on the co-production of nature's contributions to people: Insights for sustainability

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Abstract

Nature's contributions to people (NCP) broaden up the ecosystem service concept and support human life in multiple ways. These contributions are partially derived from nature together with inputs from humans, a process known as co-production of NCP. The sustainability of NCP co-production not only depends on the use of anthropogenic capitals but also on where they are produced, how they are mobilized, or the access to these capitals. In fact, NCP co-production can occur at different places and across spatial scales: it may be affected by factors not only within a system but in other systems near and far. To this end, the metacoupling framework advances the telecoupling framework and offers a lens to analyze human-nature interactions within and between systems across spatial scales. Here, we illustrate the application of the metacoupling framework on NCP co-production by using the examples of wood

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production in temperate forests in Germany, natural pest control in German meadows provided by migratory birds, and non-material NCP from giant panda tourism in China. We reflect on the challenges of adopting a metacoupling lens when analyzing NCP co-production, such as working with different disciplines and engaging with diverse knowledge systems, defining social-ecological system perimeter, or collecting metacoupled data across scales based on mixed-method approaches. While considering the relevance of metacoupling of NCP co-production for sustainability, we highlight the opportunities of adopting this lens, such as visualizing hidden and overlooked sustainability issues or making global sustainability a relevant aspect of local decisions.

1. Status

Nature's contributions to people (NCP) broaden up the ecosystem service concept and support human life in multiple ways through the provision of material (e.g., fodder and feed or building materials), regulating (e.g., pollination or carbon sequestration), and non-material (e.g., physical or psychological experiences in nature) benefits (Díaz et al., 2018). The NCP concept explicitly acknowledges that these contributions are not solely derived from nature but also require inputs from humans, a process known as NCP "co-production" (Díaz et al., 2015). As such, NCP go beyond the ecosystem services concept while embracing it (Hill et al., 2021; Kadykalo et al., 2019). Ecosystem services were originally conceptualized as unidirectional flows of benefits from ecosystems to humans, with ecosystem services located at the interface between the human and the natural systems (Haines-Young and Potschin, 2010). While we use the NCP concept because it explicitly incorporates the co-production of NCP in coupled systems of humans and nature (Bruley et al., 2021; Díaz et al., 2015); we nonetheless refer to ecosystem services literature, which has made progress in recognizing the human inputs required for the NCP co-production (e.g., Fedele et al., 2017; Lavorel et al., 2020; Palomo et al., 2016; Rieb et al., 2023). Broadly speaking co-production refers to the processes by which humans manage land and NCP to support people's quality of life by accessing and mobilizing anthropogenic capitals (Díaz et al., 2015), processes that have been increasingly investigated in the last decade (e.g., Kachler et al., 2023; Lavorel et al., 2020; Locatelli et al., 2024). These anthropogenic capitals encompass human (e.g., skills and knowledge), social (e.g., rules and institutions), physical (e.g., infrastructure or machinery), and financial capital (e.g., monetary stocks and flows) (Isaac et al., 2022; Palomo et al., 2016) (see Box 1). The sustainability

Box 1 Definitions of the anthropogenic capital types involved in nature's contributions to people (NCP) co-production based on Palomo et al. (2016) and Isaac et al. (2022).

The following capitals can contribute to – or be necessary for – the supply and flow of NCP:

- Human capital refers to people's capabilities including health, knowledge, skills, and labor used, for example, to identify medicinal plants or enjoy recreation in nature.
- Social capital includes all intangible assets associated with interactions between people, including trust, and formal and informal institutions, for example, collaborations to restore a forest.
- Physical capital refers to technological or manufactured assets, such as machinery for harvesting or transporting crops and transforming them into food.

Financial capital refers to savings, credits, and other monetary forms used for mobilizing or enhancing other anthropogenic capitals, for example, money to travel to a national park or financial investment into forest plantations.

of a coupled human and natural system (e.g., social-ecological system) largely depends on to what extent and how these anthropogenic capitals are accessed, mobilized, and used (e.g., Locatelli et al., 2024; Palomo et al., 2016; Rieb et al., 2023). For example, intensively managed farms rely heavily on inorganic pesticides, fertilizers, and heavy machinery, leading to negative environmental impacts such as biodiversity loss and pollution. Ultimately, these intensive practices threaten the long-term sustainability of these systems by reducing the capacity of ecosystems to sustain essential ecosystem functions and food production over time (Foley et al., 2005). In contrast, small organic farms use mainly organic fertilizers and nature-based pest control techniques, which tend to produce positive environmental outcomes, often maintain ecosystem functions and thus represent a more sustainable approach to agriculture (e.g., Bennett et al., 2014; Dubey et al., 2021; Foley et al., 2011; Rasmussen et al., 2024).

In an interconnected world, the anthropogenic capitals used to co-produce NCP often do not originate in the place where NCP are ultimately co-produced. In fact, NCP co-production can occur in different places and across spatial scales: it may not only be affected by factors within a geographically defined system but in other systems near and far. For example, when knowledge on carbon-sequestering agricultural practices

developed in distant research institutes is adopted by local grassland managers, NCP carbon storage is co-produced by local natural capital and flows of knowledge (human capital) across spatial scales. Similarly, soybean production in Brazil heavily depends on fertilizer imports (physical capital) from countries such as Germany and Canada (Liu et al., 2018). Although a growing body of research shows the importance of analyzing the telecoupled flows of NCP between distant sending and receiving systems, that is, between the system where the NCP is provided and systems where the NCP is used (e.g., Brück et al., 2023; Drakou et al., 2018; Kleemann et al., 2020; Schirpke et al., 2019; Wang et al., 2022), the telecoupled flows of the anthropogenic capitals that underpin NCP co-production remains largely unknown, with important consequences for assessing the sustainability of a system (Koellner et al., 2019; Schröter et al., 2018).

The metacoupling framework (Liu, 2017), which advances the telecoupling framework, can provide a holistic perspective to account for the coupled flows underpinning the use of anthropogenic capitals. *Metacoupling* encompasses all types of coupling between people and nature, including (1) *intracoupling* which refers to those human-nature interactions within a geographically defined system (e.g., wood harvesting in a county), (2) *pericoupling* or those human–nature interactions between adjacent systems (e.g., the export of harvested wood to a neighboring county), and (3) *telecoupling* referring to those human-nature interactions across distant systems (e.g., the export of harvested wood to another continent) (Liu, 2023, 2017).

Peri- and telecoupled flows of anthropogenic capitals link adjacent and distant systems and actors, for example by transferring knowledge (Carlson et al., 2018), shaping social norms (Carrasco et al., 2017), making agricultural technology accessible (Zimmerer et al., 2018), and facilitating foreign investments (Zaehringer et al., 2018). However, these metacoupled capital flows are often investigated in isolation without considering their interplay with each other and nature. Examining the interplay of metacoupled anthropogenic capitals and their roles in the co-production of various NCP is crucial for gaining a deeper understanding of the sustainability of these processes.

Using the metacoupling framework to study NCP co-production (Fig. 1), the focal system is conceptualized as an intracoupled system that integrates natural capital (e.g., forests, grasslands, and biodiversity) with anthropogenic capital (e.g., financial resources, tools, knowledge, and social networks) to co-produce NCP (e.g., wood, climate regulation, and cultural identities). Drawing on the examples of wood (Box 2), pest control by migratory birds

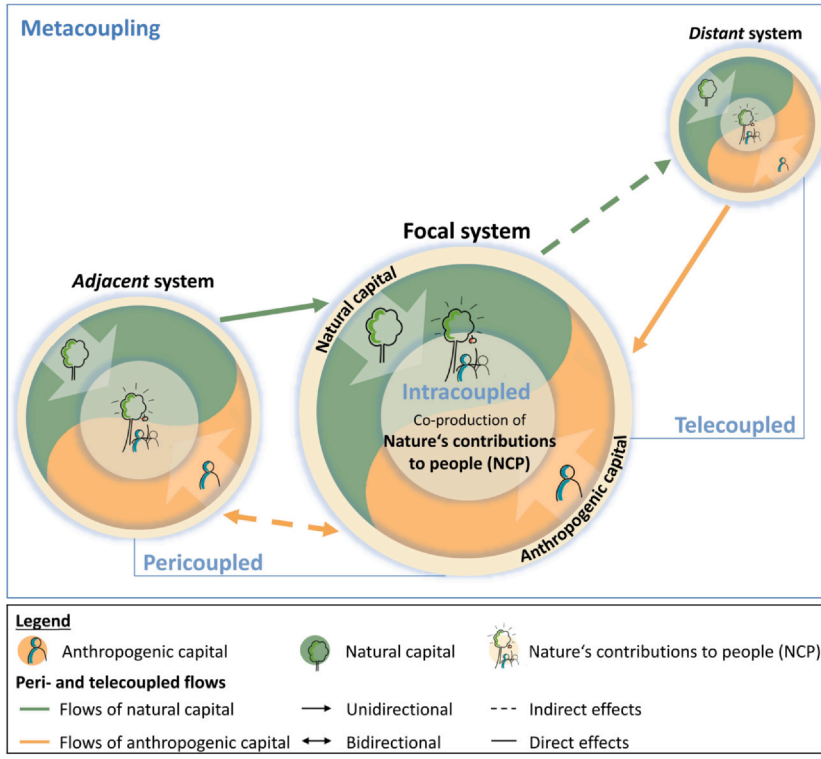

Fig. 1 Visualization of the **metacoupling lens** (Liu, 2023, 2017) on the co-production of nature's contributions to people (NCP) within and across spatial systems. **Intracoupling** represents the co-production of NCP within a single social-ecological system, driven by the interplay of natural and anthropogenic capital (Isaac et al., 2022; Palomo et al., 2016). **Pericoupling** describes capital and NCP flows between adjacent systems. **Telecoupling** illustrates these flows between distant systems. Arrows represent the direction of flows from sending to receiving systems: solid arrows indicate flows that directly influence NCP co-production in the focal system and dashed arrows indicate flows that have indirect effects. Flows can be **unidirectional or bidirectional**, depending on the nature of the interactions between systems. For simplicity, additional spillover systems—those influenced by or influencing these flows—are not depicted but remain critical for consideration. Each system also includes **causes** (drivers of the flows), **agents** (decision-making entities facilitating the flows; here referred to as actors), and **effects** (ecological and socioeconomic outcomes).

(Box 3), and non-material NCP from giant panda tourism (Box 4), we illustrate the application of the metacoupling framework on NCP co-production. We then discuss the challenges and opportunities associated with applying this lens to NCP co-production, while reflecting on the relevance of considering metacoupling of NCP co-production for sustainability.

Box 2 Wood production in temperate forests in Germany.

Wood is an important NCP in German forests as it supports private and public (e.g., state or municipality) forest owners who rely on wood sales for income (Lovrić et al., 2025; Mann et al., 2022). Wood is co-produced by an interplay of natural capital and several anthropogenic capitals (Fig. 2) (Isaac et al., 2024).

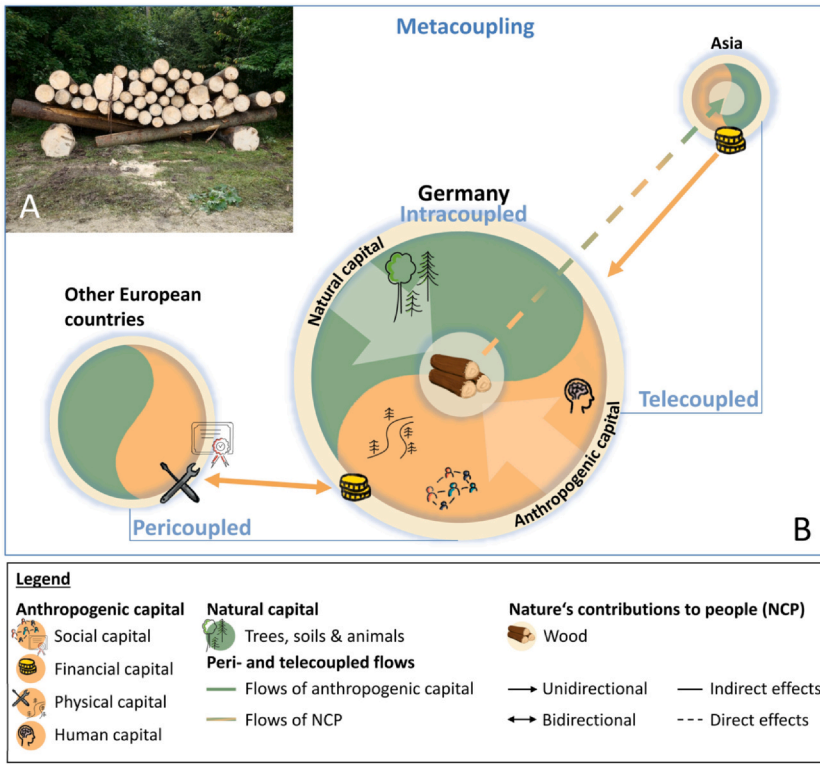

Fig. 2 (A) Photo of recently harvested wood ready for shipment taken by Roman Isaac in the Biosphere Reserve Schwäbische Alb, Germany. (B) Representation of metacoupling in wood production in German forests. The figure is not intended to be exhaustive, but rather intended to provide an overview of the metacoupling in this particular NCP co-production.

Intracoupling of natural and anthropogenic capitals.

Natural capital includes trees, soils, and animals that support the dispersal of seeds and the growth of the trees. Intracoupled anthropogenic capitals include the forest managers' knowledge and skills, their local social networks, and the local infrastructure that permits access to forest patches, such as forest roads and skid roads.

Peri- and telecoupled anthropogenic capitals.
Wood production relies on peri- and telecoupled flows of anthropogenic capitals. Machinery used for harvesting, such as harvesters, forwarders, or chainsaws, is mainly imported from other European countries or globally. Contractors employed in harvesting often come from other European countries (Isaac, 2024). Financial support for forest owners is provided by the German federal government and federal states to maintain forest roads used for harvesting and transport or to deal with calamities due to extreme weather or bark beetle infestation (Sotirov and Storch, 2018). Forestry certification at the national and international level, such as the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC), provide guidelines for sustainable forest management practices and are often adopted to improve wood and wood marketization (Zubizarreta et al., 2021).
Peri- and telecoupling of wood.
Harvested wood is either processed in local sawmills and then sold locally, for example, as building material, or processed and then shipped to other countries in Europe or even Asia. For example, wood harvested in Germany may be processed elsewhere and then re-imported as furniture or dashboards used in auto manufacturing.

2. Current challenges

Despite a growing body of literature on metacoupling (e.g., Carlson et al., 2020; Jia et al., 2024; Liu, 2023; Manning et al., 2023; Schaffer-Smith et al., 2018; Xiao et al., 2024; Zhao et al., 2018) and recent theoretical and empirical advancements on the interactions of natural and anthropogenic capitals in NCP co-production (e.g., Locatelli et al., 2024; Rieb et al., 2023), several challenges for employing a metacoupling lens on NCP co-production remain. Here we explore five of these challenges:

- **Working with different disciplines and engaging with diverse knowledge systems.** Engaging with NCP co-production and metacoupling calls for broadening scholars' ontological spaces, that is, their understanding of what exists and how humans and nature interact. This requires simultaneously navigating different theories, disciplines, and bodies of knowledge, that together are better suited to working with complex social-ecological dynamics (Mancilla García et al., 2020). Bringing together different bodies of knowledge and disciplines (such as

Box 3 Natural pest control in German meadows provided by migratory Northern Lapwing (*Vanellus vanellus*).

The natural pest control provided by the migratory Northern Lapwing (*Vanellus vanellus*) minimizes the need for human inputs such as pesticides in German meadows and results out of the interaction between natural capital and diverse anthropogenic capitals (Fig. 3).

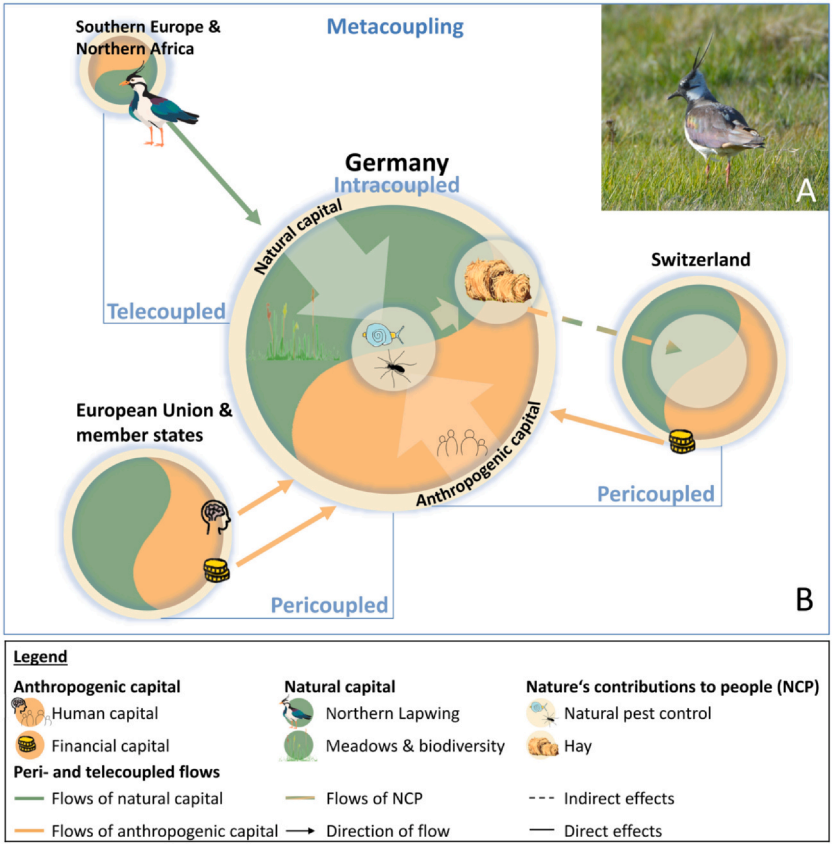

Fig. 3 (A) Photo of the northern lapwing (*Vanellus vanellus*) taken by Berta Martín-López in the Untere Seeveniederung nature reserve in Lower Saxony, Germany. (B) Representation of metacoupling in natural pest control in German meadows provided by migratory birds. The figure is not intended to be exhaustive, but rather intended to provide an overview of the metacoupling in this particular NCP co-production.

Intracoupling of natural and anthropogenic capitals.
Between 1990 and 2018, the lapwing population in Germany decreased by more than 80%, owing mostly to agricultural intensification (Kamp et al., 2021; Plard et al., 2020). While lapwings prefer to nest on extensively farmed, open wet grassland, intensive agricultural cultivation leads to habitat desertification, a high risk of nest destruction and a low survival rate of chicks, as the grassland is often too dense and mowed too regularly (Buschmann et al., 2023). Natural capital in the co-production of natural pest control includes the lapwing populations that migrate to Germany from Southern Europe and Northern Africa, the meadow ecosystems that host insect pests as feed for the lapwing, and the wider biodiversity that supports ecological balance. Intracoupled anthropogenic capitals include, among other things, the knowledge of farmers who manage these meadows to maintain favorable conditions for nesting and foraging, and the financial resources to maintain these extensive management practices that may lead to less grass harvest.
Peri- and telecoupled natural and anthropogenic capitals.
Pest control by lapwings in German meadows is influenced by peri- and telecoupled flows of natural and anthropogenic capitals. Regarding natural capital, lapwings migrate in spring from Southwestern Europe and Northern Africa to Germany. Regarding human capital, research, and development of farming techniques compatible with biodiversity conservation, often developed in academic institutions or agricultural organizations abroad, are adopted by local farmers. Concerning financial capital, subsidies, or support schemes, such as agri-environmental schemes, are often introduced at national or European level to encourage conservation-friendly farming practices. The primary goal of these programs is to financially compensate farmers for the expenses and revenue lost while adopting such measures on their land (Buschmann et al., 2023).
Peri- and telecoupling of hay (a material NCP) derived from management practices that rely on natural pest control.
The extensively managed grasslands that are favored by lapwings are typically characterized by a lack of nutrients, which results in hay with a low nutrient content. This makes it less suitable for livestock such as cattle or sheep, but highly valuable for horses, which can thrive on such roughage. Hay harvested on German grasslands, but with the benefit of lapwing pest control, can be used locally - supply often exceeds local demand, leading to export to peri- or distant markets, such as Switzerland. For farmers who engage in these natural pest control practices, selling to these markets represents an additional source of income that can be used to maintain these practices.

Box 4 Non-material NCP from giant panda (*Ailuropoda melanoleuca*) tourism in China.

Non-material NCP from giant pandas (*Ailuropoda melanoleuca*) result from the coupling of natural and anthropogenic capitals (Fig. 4). Here, we focus on couplings related to eco-tourism, which contributes to the co-production of several non-material NCP from pandas, such as learning and inspiration, psychological experiences, or supporting identities (Liu et al., 2016).

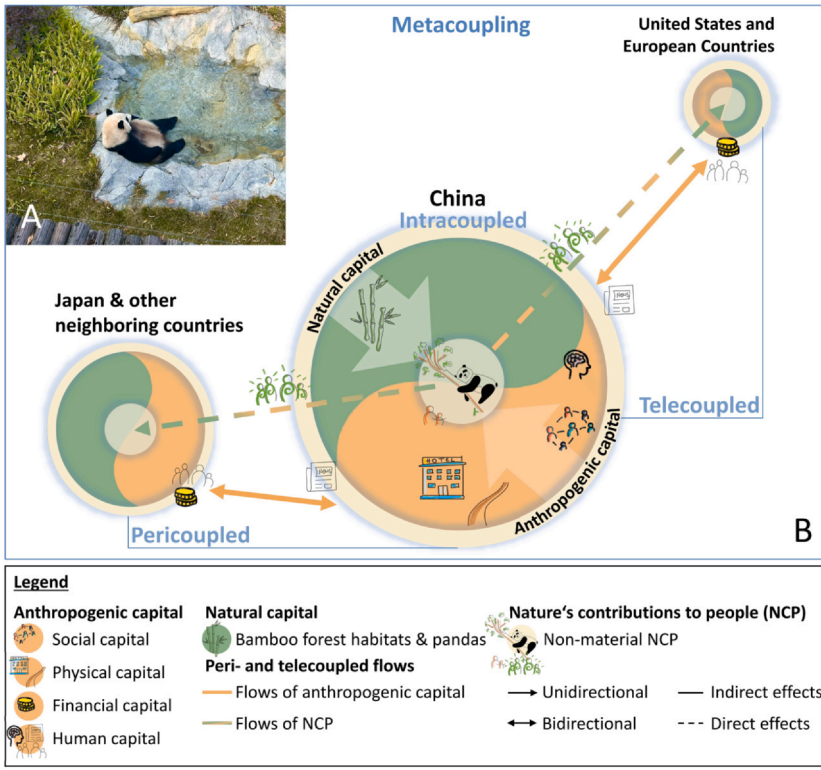

Fig. 4 (A) Photo showing a giant panda taking a bath captured by Katharina Göhl in Chengdu, China. (B) Representation of metacoupling in ecotourism for giant pandas in China. The figure is not intended to be exhaustive, but rather intended to provide an overview of the metacoupling in this particular non-material NCP co-production.

Intracoupling of natural and anthropogenic capitals.
Natural capital encompasses the pandas themselves, their bamboo forest habitats, and the broader ecosystems and landscapes supporting the survival of bamboo, and other plants, such as canopy trees that provide important shade for the understory bamboo. Intracoupled anthropogenic capitals include the expertise of conservationists, eco-tourism operators and tour guides (human capital), the involvement of government officials and local communities in habitat conservation (social capital), and infrastructure like panda reserves, restaurants, hotels, trails, and resting areas (physical capital). Together, these capitals offer opportunities for visitors to appreciate giant pandas and their habitats, establish an emotional connection to pandas, and promote sustainable eco-tourism practices for biodiversity conservation and economic development.
Peri- and telecoupled natural and anthropogenic capitals.
Non-material NCP depend on peri- and telecoupled flows of anthropogenic capitals from places near and far. For eco-tourism, information about pandas in the Wolong Nature Reserve of southwestern China is disseminated to other countries around the world through news media outlets (Liu et al., 2015). Such information facilitates tourists from both neighboring countries, such as Japan, and distant countries such as the United States and European countries, to visit Wolong (Liu et al., 2015). Many countries and international organizations including the World Wildlife Fund (WWF) also provide funding for panda conservation, which in turn helps sustain eco-tourism.
Peri- and telecoupling of non-material NCP from giant pandas.
Peri- and telecoupling of non-material NCP from giant pandas through eco-tourism are made possible by tourists from neighboring countries such as Japan and distant countries such as the United States and European countries visiting nature reserves for giant panda conservation like Wolong Nature Reserve (Liu et al., 2016).

metacoupling and NCP co-production, which include, among others, systems ecology, landscape ecology, spatial economics, geography, ecosystem services and sustainable livelihoods literature) entails dealing with diverse theories informed by different ways of being (i.e., ontological perspectives) and ways of knowing (i.e., epistemological perspectives) (Hertz and Schlüter, 2015; Kuhn, 1970). In doing so, scholars are required to practice epistemological agility, defined as "an understanding of different ontological and epistemological standpoints and views across multiple disciplines, enabling better communication and collaboration

with different researchers, and facilitating open interdisciplinary practice for individuals and within research teams" (Haider et al., 2018). Such skills can contribute to overcoming a typical challenge of complex sustainability challenges: the lack of a common way of communicating and terminology that is understood across the multiple disciplines involved in metacoupling and NCP co-production, which often leads to misunderstandings (Strang, 2009; Turnhout, 2019) and persistent ambiguities (Lazurko et al., 2024; Preiser et al., 2018). Working with different disciplines and engaging with diverse knowledge systems, allows scholars to engage with the complexity, dynamism, and intertwined nature of human–nature interactions (Bennett and Reyers, 2024), present in the metacoupled nature of NCP co-production.

- **Dealing with hard-to-define social-ecological system perimeter.** Social-ecological systems are embedded and nested within larger systems and characterized by porous boundaries that allow the exchange of matter, information, and energy (Bennett and Reyers, 2024). As a result, defining the focal, receiving, and sending systems for a metacoupling analysis can be challenging. This challenge is even more prominent if we consider the anthropogenic and natural capitals underlying the provision of an NCP and how an NCP is mobilized to contribute to people's quality of life elsewhere. For example, an agricultural system that provides food for the global market requires both soil ecosystem functions, such as nutrients cycling, and human labor. While nutrient cycling is a local process tied to the soil, human labor often originates from nearby urban areas. This interconnectedness illustrates the challenge of drawing clear boundaries between the agricultural system of focus and its surroundings. Yet, new directions in social-ecological systems research suggest that defining, testing, and constantly reviewing the system boundaries (Preiser et al., 2018) might support the definition of coarse and porous boundaries of the systems involved in the metacoupling of NCP co-production.
- **Collecting metacoupled data across scales based on mixed-method approaches.** To operationalize the metacoupling framework in the context of NCP co-production, data gaps need to be filled. Quantitative data on peri- and telecoupled flows in NCP co-production are often only available at the national scale, but are lacking at finer scales such as municipality or county (Koellner et al., 2019). Since NCP co-production processes may vary between regions within a country, making them more or less peri- and telecoupled, focusing on the national level may disguise

important causes and effects of metacoupling. Obtaining comparable place-based data, e.g., via surveys, could provide additional information relevant to bridging this data gap (Hubacek et al., 2014). This may include data sharing, e.g., through open data repositories that allow access and analysis of available (anonymized) qualitative and quantitative NCP co-production data. However, similar to the challenges of quantifying the flows of non-material NCP (Schröter et al., 2018), quantitatively assessing non-material anthropogenic capitals contributing to NCP co-production remains difficult, particularly for flows of human and social capital, such as knowledge or trust (Kachler et al., 2023). Even though recent co-production analyses have quantified natural and anthropogenic inputs using simple indicators, such as synthetic fertilizers (in kg/ha) as a measure of anthropogenic input to crop production (e.g., Locatelli et al., 2024), fully understanding the metacoupled flows of anthropogenic capitals does not solely rely on quantification. Qualitative approaches such as interviews, focus group discussions, or participatory mapping techniques (e.g., public participation geographic information system (PPGIS)) provide important opportunities to consider the nuanced nature of metacoupled flows (Busck-Lumholt et al., 2022; Nielsen et al., 2019). Empirical research conducted by the authors, involving interviews with actors engaged in NCP co-production processes in German forests and grasslands, highlights the value of qualitative methods in elucidating peri- and telecoupled flows of anthropogenic capital including social and human capital as well as causes and effects of peri- and telecoupling. For example, farmers described how they rely on knowledge (human capital) from distant research institutes (telecoupling) to ensure bird nesting habitats (Box 3) and foresters described how they found their communities (social capital) through nationwide (pericoupling) training programs (human capital) run by certification bodies and how this shaped their management practices (Box 2). Mixed-methods approaches can thus facilitate a more holistic understanding of metacoupled anthropogenic capital flows in NCP co-production.

- **Tracing the relations among social actors behind NCP co-production.** Globalized NCP supply-chains, e.g., wood as a building material (Box 2), consist of manyfold processing steps, managed by a variety of actors. Traders, processors, retailers, consumers, investors, credit providers, regulators, NGOs linked to sustainability agendas, all influence how producers operate. Such operational complexities can often mask unsustainable practices and lead to an unfair attribution of responsibilities (Zyglidopoulos and Fleming, 2011). For example, shifting investments in a 'free trade'

environment may allow transnational actors to avoid responsibility for operations within local jurisdictions. To have on-the-ground changes on the sustainability of NCP co-production within globalized supply-chains, Gardner et al. (2019) propose a cyclical process of supply chain assessment and governance intervention based on transparent information: (1) information on associations among actors and between actors and places that trace not only actors' identities but their role and the nature of their connections (including power implications of contractual relationships); (2) transaction information on purchasing practices, including sales of inputs to the production process, and economic investments and ownership, including actors outside the primary supply-chain; (3) information on environmental and social impacts of specific supply-chain stages; (4) information on the policies and commitments of the supply-chain actors to increase the sustainability of their operations, including how performance will be assessed; (5) information in terms of production, sales, purchasing, processing and investment decisions that report on actors actions to meet their sustainability policies and commitments; and (6) information on effectiveness of interventions to improve performance of a given actor or production/processing location. Governance arrangements involving multiple actors, such as state, civil society, and private actors, can influence complex transnational connections through interventions (e.g., incentives, access to information, policy instruments) that may build up to the role of local jurisdictions (Bush et al., 2015). For example, national governments can regulate standardized sustainability reporting requirements, while civil society groups such as research institutions and NGOs can contribute to monitoring effectiveness of interventions and actors' activities. However, it is important to trace the relations among actors along the supply-chain to avoid potential harm from transparent information becoming an end in itself (e.g. actors withdrawing from high environmental risk areas, usually low-income countries, and excluding from the market the very places that need attention and economic activity) (Gardner et al., 2019). Instead, such information reinforces the need for collective action to make it a means to an end – more sustainable NCP co-production.

- **How to achieve desirable sustainability outcomes that are fair for all.** Research on the effects of global trade on the Sustainable Development Goals revealed that metacoupling had distinct consequences in developed and developing countries (Xu et al., 2020). In a metacoupled world, the interactions between intra-, peri-, and telecoupling are complex and spillover effects are prevalent (Liu, 2023). Due to the adaptability of complex

social-ecological systems and the nature of sustainability problems, deeply interconnected, and with no clear or simple solutions, large uncertainties will remain regarding scalability and transferability of sustainable processes (Lam et al., 2020). In this light, recent social-ecological systems research advocates for embracing uncertainty resulting from non-linear and unpredictable human-nature interactions. Rather than identifying specific sustainable solutions, the focus should shift to navigating the associated processes (Bennett and Reyers, 2024), yet with a strong emphasis on analyzing justice and power dimensions. Although recent literature has already identified that a better understanding of justice requires analyzing diverse dimensions for all NCP, including supply, demand and use of NCP, access to NCP, and benefit from NCP (e.g., Brück et al., 2024; Langemeyer and Connolly, 2020; McDermott et al., 2013; Nyelele and Kroll, 2020), and the capitals underlying their provision (e.g., Fischer and Eastwood, 2016; Langemeyer et al., 2024; Loos et al., 2023), NCP co-production is missing the justice lens in the assessment of its metacoupled flows (Li et al., 2023). Moreover, such view is relevant since a time lag of unintended side effects often emerges, plus these negative consequences occur in places far from the original action (Ingalls et al., 2018). Research on justice and NCP has already advanced knowledge by investigating the decision-making processes underpinning the extraction and distribution of NCP, and the management of NCP co-production (Loos et al., 2023). In fact, Loos et al. (2023) show that meaningful engagement with social actors and rights-holders is critical to identifying the contextual factors that influence justice outcomes. Yet, it is also important to consider who (which actor at which scale) has the power to make decisions, for example, about subsidies for certain management practices that promote a set of NCP in detriment of others and, thus, favoring some actors over others. An in-depth understanding of justice should therefore also uncover potential power imbalances in decision-making over NCP and the capitals underpinning their provision across scales and metacoupled flows (Martín-López et al., 2019; Shackleton et al., 2023).

3. Opportunities

Employing a metacoupling perspective creates opportunities to better understand potential trade-offs resulting from NCP co-production processes based on interactions with adjacent and distant systems. Here we outline five opportunities for future research:

- **Visualizing hidden and overlooked sustainability issues.** NCP co-production analyses have already highlighted adverse impacts in the focal system itself (e.g., pollution or natural capital degradation) and the resulting trade-offs, for example, if the co-production of one NCP hinders the co-production of another (Lavorel et al., 2020; Rieb et al., 2023). The metacoupling perspective reveals unintended social and environmental spillover effects of these processes on distant and adjacent regions (e.g., child labor, pollution, emissions from transportation). Together, co-production and metacoupling perspectives enable a more holistic understanding of how local and global processes influence the sustainability and equity of NCP. They help visualize hidden and overlooked sustainability issues (Li et al., 2023).
- **Accounting for responsibilities and boosting agency.** Global power imbalances often lead to ecologically unequal exchanges in the metacoupling of NCP co-production, where unequal transfers of capitals are hidden in telecoupled flows (Dorninger et al., 2021). Only by understanding these telecoupled flows, responsibilities for social-ecological outcomes can be identified and local agency over NCP co-production can be enabled. For distant actors, it raises awareness of their accountability for telecoupled impacts, such as when conservation areas imposed to offset projects disrupt local cultures and livelihoods (Anaya and Espírito-Santo, 2018), or when material NCP extraction harms health through production methods and their influence on social determinants of health, such as employment and living conditions (Anaf et al., 2019; Svampa, 2019). In resisting imposed metacoupling, marginalized groups form social capital flows through transnational networks and alliances that can boost their agency over the process (Muñoz, 2006). Examining discrepancies between who co-produces NCP and who controls metacoupled flows (Dou et al., 2020) can help regulate metacoupled activities, ensure accountability, and empower local actors to align NCP co-production with their priorities.
- **Shedding light on environmental justice and equity.** Since capitals are naturally unequally distributed and their mobilization is tightly linked to histories of innovation and domination, considering justice and equity is key to enhancing the sustainability of metacoupling flows of NCP co-production. An opportunity to implement considerations of justice and equity arises through conceptualizing and empirically researching the procedural mechanisms underlying the metacoupled flows of anthropogenic capitals in NCP co-production, as well as the outcomes of these

mechanisms in terms of distributive justice. In this sense, the metacoupling framework can shed light on the three dimensions of environmental justice, as recognized in the literature: (1) recognitional justice or recognizing the diversity of people's views on the issue at hand (Martin et al., 2016); (2) distributional or distributive justice, which refers to the equitable allocation of and access to costs and benefits for all social actors (Schlosberg, 2013); and (3) procedural justice, which refers to participation and representation in decision-making processes (Fraser, 2009). For example, the vast majority of economic benefits from ecotourism in Wolong Nature Reserve for panda conservation (Box 4) went to the tourism industry rather than the local residents who bear the primary costs of conservation (He et al., 2008). Looking at the three dimensions of environmental justice through the metacoupling lens in the case of panda conservation in Wolong, we can explore *recognitional justice* by considering the traditional ecological knowledge of local communities, *distributive justice* by examining the unequal sharing of economic benefits from eco-tourism, and *procedural justice* by assessing residents' representation in decision-making processes at all scales. Employing a metacoupling lens could shed light on the social inequalities that might arise from the intra-, peri- and telecoupled flows of NCP and the capitals underpinning their co-production by understanding the decision-making mechanisms as well as the distribution of benefits and costs in the places of origin and destination. This information could provide insights on which changes, where, and by whom are necessary for leveraging equity and justice.

- **Better understanding of decision-making contexts.** Metacoupled flows of NCP and anthropogenic capitals challenge traditional governance since they transgress jurisdictional boundaries (Liu, 2023). Research has conceptualized the interlinkages between governance approaches and metacoupling more generally (e.g., Cotta et al., 2022; Lenschow et al., 2016; Newig et al., 2020, 2019; Oberlack et al., 2018), and focused on more specific implications, for example, for conservation (e.g., Carmenta et al., 2023; Carrasco et al., 2017), food systems (e.g., Eakin et al., 2017), NCP provision (e.g., Martín-López et al., 2019), and global commodity flows (e.g., Coenen et al., 2023; Marques et al., 2024). Governance can be active in favoring or reactive to the different forms of metacoupling and the resulting consequences. For example, governance arrangements may "induce(s) telecoupling" by creating circumstances that facilitate the establishment of telecoupled connections, it may "coordinate(s) telecoupling" through chains of actors, or simply "respond(s) to

telecoupling" to minimize its negative effects (Newig et al., 2019, p. 2). Governance responses to these negative effects remain challenging due to existing knowledge gaps concerning relevant knowledge for decision-making (e.g., regarding land-use changes due to telecoupling such as deforestation due to soy cultivation), opposing interests between and among state and non-state actors, increased transaction costs, legitimacy issues and persistent power asymmetries, and lacking policy coherence (Newig et al., 2020). So far, research on governing anthropogenic capitals in NCP co-production has focused on isolated drivers of capital use (Isaac et al., 2024, 2022). Identifying how governance arrangements deal with the negative externalities of telecoupled NCP and capital flows can prove beneficial when trying to understand how and why co-production decisions are made regarding the use of specific anthropogenic capitals. In turn, a more specific analysis of the motives of NCP co-producers can inform better decision-making and policy.

- **Integrating global sustainability in local decisions.** The dual perspective on co-production and metacoupling is an opportunity to make global sustainability a relevant aspect of local decisions (Mastrángelo et al., 2019). Without a metacoupling perspective, many sustainability issues in the co-production of NCP are hidden, including invisible injustices but also social and planetary boundaries. The safe and just space of social and planetary boundaries (also known as the doughnut model) encourages decision-makers to design policies that remain within ecological ceilings while lifting people above social foundations (Raworth, 2017). Analyzing metacoupling in NCP co-production can identify whether addressing a planetary boundary (e.g., climate change or biodiversity loss) or a social boundary (e.g., food security, health, or social equity) in a local system undermines planetary and social boundaries elsewhere (Brand et al., 2021; Li et al., 2021).

4. Conclusion

With this paper, we have tried to make the point that NCP co-production occurs at different scales - local (intra), near (peri-) and far (telecoupling) - which is important to consider when assessing the sustainability of social-ecological systems. Research on NCP co-production needs to embrace interdisciplinary approaches and multiple perspectives to fully capture the interconnectedness of these systems. The inherent fluidity of social-ecological systems presents challenges in clearly defining their

components and boundaries, as these systems are constantly evolving. To address this, more quantitative but also qualitative data is needed to capture the nuanced interactions and processes involved in NCP co-production at different levels. The metacoupling approach offers valuable insights into how we can think across scales to ensure that no important elements are overlooked, while also promoting greater accountability and different forms of justice.

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Disclosure statement

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