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Promoting sustainable development worldwide in the metacoupled anthropocene

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Qutu Jiang [1], Zhenci Xu [1,2], Nishan Bhattarai [3], Yinyi Lin[1], Huijuan Xiao [4], Jingzheng Ren [5], Markus Pahlow [6], Zhimeng Jiang[1], Yali Liu [7], Xutong Wu [8], Guanqiong Ye [9], Hongsheng Zhang [1], Jinbao Li [1], Peng Zhu [1], Shunlin Liang[1], Yuanzheng Cui[10], Chuan Liao [11], Liang Dong [12] & Jianguo Liu [13]

Promoting sustainable development worldwide requires collaborative efforts across interconnected systems under integrated frameworks. Here, we illustrate the integrated metacoupling framework as a holistic lens for analyzing human-nature interactions within and between systems to advance integrated sustainability analysis. We propose six interrelated steps to operationalize the framework for Sustainable Development Goals' interaction analysis, progress assessment, and pathway modeling, contributing to the integration of knowledge for the 2030 Agenda and emphasizing "Leave No One Behind". We demonstrate that the framework offers interdisciplinary researchers a practical toolkit and supports policymakers in developing synergistic cross-system strategies for sustainable development across local to global scales.

The 2030 Agenda outlined 17 Sustainable Development Goals (SDGs) to achieve sustainability everywhere (e.g., "End poverty in all its forms everywhere"), emphasizing the principle of "Leave No One Behind"[1]. Despite some accomplishments in achieving SDGs in the last decade, the world continues to struggle with a wide range of sustainability challenges to achieve the SDGs, including poverty, inequality, climate change, and biodiversity loss[2–5]. These challenges are further complicated in the metacoupled Anthropocene, where coupled human and natural systems[6] (e.g., nations, regions, or cities in which human and natural components interact dynamically) are interconnected through flows and feedback loops across various distances and scales[7]. This multiscale and cross-system interdependence exists not only locally, but also regionally and globally[8,9], meaning that local sustainability interventions can have far-reaching regional and global sustainability outcomes and vice versa[8,10,11].

To effectively navigate complex sustainability challenges, a deeper theoretical understanding and enhanced analytical frameworks are essential for examining human-nature interactions across systems and scales, as well as their sustainability implications. For example, through international trade, nations outsource environmental costs, shift economic investments and displace social impacts beyond their borders[12,13], creating transboundary effects that may either promote or hinder SDG progress in nearby or distant countries[14,15]. Global shocks—sudden, widespread disruptions such as pandemics and armed conflicts that trigger cascading and far-reaching impacts that can substantially reverse SDG attainment. Their effects on different goals are

[1]Department of Geography, The University of Hong Kong, Hong Kong, China. [2]Institute for Climate and Carbon Neutrality, The University of Hong Kong, Hong Kong, China. [3]Department of Geography & Environmental Sustainability, University of Oklahoma, Norman, OK, USA. [4]Department of Geography, Hong Kong Baptist University, Hong Kong, China. [5]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China. [6]Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand. [7]School of Grassland Science, Beijing Forestry University, Beijing, China. [8]State Key Laboratory of Earth Surface Processes and Disaster Risk Reduction, Faculty of Geographical Science, Beijing Normal University, Beijing, China. [9]Ocean College, Zhejiang University, Zhoushan, China. [10]Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China. [11]Department of Global Development, Cornell University, Ithaca, NY, USA. [12]Department of Public and International Affairs, and School of Energy and Environment, City University of Hong Kong, Hong Kong, China. [13]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA. e-mail: xuzhenci@hku.hk; liuji@msu.edu

complex across multiple interconnected systems[16]. For instance, the COVID-19 pandemic drastically hindered socioeconomic progress in economy (SDG 8), health (SDG 3), poverty eradication (SDG 1), and education (SDG 4)[17], yet simultaneously generated temporary environmental benefits. Lockdowns and reduced economic activities led to reduced emissions and improved air and water quality worldwide, which benefits environmental goals such as climate action (SDG 13) and land-ocean conservation (SDGs 14 & 15)[18–21]. The Russia-Ukraine war has profound impacts on global energy (SDG 7) and food systems (SDG 2)[22,23], which also led to compensatory cropland expansion in other distant countries, driving biodiversity loss far from war zones (SDG 15)[24].

Despite growing recognition and research of cross-system interdependencies and their implications for the SDGs, most studies remain fragmented, focusing either on isolated systems or bilateral distant connections[8,25–27], rather than adopting an integrated, multi-scale framework. This gap limits systematic understanding and effective governance of interconnected systems, ultimately hindering progress toward global sustainability. The metacoupling framework[9] addresses this gap by advancing a holistic systems approach that explicitly differentiates and integrates three key dimensions of human-nature interactions : within a system (intracoupling), between adjacent systems (pericoupling), and between distant systems (telecoupling[8]). By capturing these multi-scale dynamics, the framework enables systematic analysis of how sustainability interventions in one system generate ripple effects in others, revealing complex SDG interactions and their transboundary consequences across systems. With its broad applicability[28–32], the framework provides a powerful tool for studying human-nature interactions and related sustainability challenges worldwide, offering insights to promote the SDGs worldwide while upholding the principle of "Leave No One Behind".

This paper elucidates the metacoupling framework as an integrative analytical lens, systematically examining its theoretical structure, functional components, methodological advantages, and operationalization steps through practical demonstrations for addressing interconnected sustainability challenges and advancing SDG analysis. The study is structured as follows: (1) an overview of the concepts and the framework of metacoupling, (2) an examination of its potential as a grounded analytical lens for researchers to systematically analyze cross-scale and cross-system SDG interactions, progress, and pathways, (3) a demonstration of operationalizing the framework in sustainability research with outlined operational steps using China's Guangdong-Hong Kong-Macao Greater Bay Area as a schematic case, and (4) a discussion of current challenges and future research directions. We hope that this paper will help equip researchers to conduct holistic cross-system SDG analysis and assist policymakers in formulating collaborative policies and actions for sustainable development worldwide.

The concept and framework of metacoupling and sustainability implications

Overview of the metacoupling framework

Human-nature interactions are becoming highly interconnected and complex across the local to global scales in the Anthropocene, which critically shapes sustainability[19,33–36], represented by the 17 UN SDGs. Changes in a specific system (e.g., a country or a city) affect not only that system but also other systems nearby and far away, thereby influencing global progress toward the SDGs. For instance, countries degrade the nature within their borders by clearing land for various purposes such as agriculture and urban development, while also driving habitat and biodiversity loss beyond their borders through the import of agricultural products grown in nearby and distant regions[37]. The demand for marine sand from rapidly urbanizing cities degrades biodiversity through intensive extraction practices, creating complex social and ecological impacts far from the cities where the sand is consumed[38]. Effectively managing such cross-scale and cross-system dynamics requires a systematic framework to better understand and prioritize interactions most relevant to sustainable development.

Building upon and expanding research on coupled human and natural systems (CHANS)[6,39–41], the metacoupling framework was published in 2017 to systematically address human–nature interactions (couplings) within as well as between adjacent and distant systems[9]. Metacoupling consists of intracoupling, pericoupling, and telecoupling. (1) Intracoupling refers to human-nature interactions within a system. (2) Pericoupling and telecoupling describe interactions between two or more systems, differing in their spatial proximity: pericoupling occurs among adjacent systems, whereas telecoupling spans distant systems[8] (Fig. 1). The metacoupling framework synthesizes three types of couplings into a unified structure to analyze human-nature interactions within and among systems over space, as well as their implications for achieving the 17 SDGs. Moreover, this framework explicitly incorporates time as a core analytical dimension to capture the complex evolution of dynamic human-nature interactions[9,15,42,43]. It facilitates the examination of temporal features such as time lags, dynamic patterns, and legacy effects, while highlighting feedback loops and nonlinear processes across intra- peri-, and telecouplings. For instance, shifting tourism flows and conservation policies reshape panda habitat interactions over time[29,31]; decades of change in global fishing patterns connect coastal waters to distant oceans[43,44]; and long-term international trade reconfigures sustainability outcomes between developing and developed nations[14,15]. The explicit treatment of time ensures the framework captures the dynamic nature of sustainability challenges, moving beyond static snapshots to reveal continuous and evolving interactions that provide essential knowledge for crafting adaptive, effective, and sustainable policy-making.

This framework comprises five interrelated components—systems, flows, agents, causes, and effects (see Table 1 for detailed definitions):

(1) A metacoupled system consists of an interrelated set of systems that are connected through various flows and form feedbacks among them. Spatially, systems can be treated as focal, adjacent and distant systems by their proximity (Fig. 1). System boundaries are flexibly defined within the metacoupling framework, relying on spatial proximity (e.g., physically Euclidean distance) or political/administrative borders (e.g., national jurisdictions). For instance, trade between neighboring countries sharing the same border constitutes pericoupling, while international trade across continents represents telecoupling[11,15]. This spatial distinction enables researchers to examine how metacoupling effects vary across scales, given the fact that the patterns and magnitudes of impacts often differ substantially between short-distance and long-distance interactions across geographies[37].

(2) Spillover systems are those indirectly affected by or influence human-nature interactions within or between other systems without being directly involved in flows connecting them (Fig. 1). Spillover effects can arise from intra-, peri-, and tele-couplings, though often overlooked, have profound implications for the SDGs[45]. For example, countries experiencing the effects of carbon emissions and global warming due to trade and consumption in other nations can be treated as spillover systems.

(3) Flows within and between systems are diverse, such as physical flows (e.g., goods, materials, human migration, pollutants), non-material flows (e.g., services, information, technology), and virtual flows (e.g., embedded virtual water, carbon emissions, nitrogen)[34,46–48]. Systems can both send and receive these flows, the magnitude and direction of which is critical to measure the intensity of interactions among metacoupled human-natural systems. The determination of flows to focus on is often guided

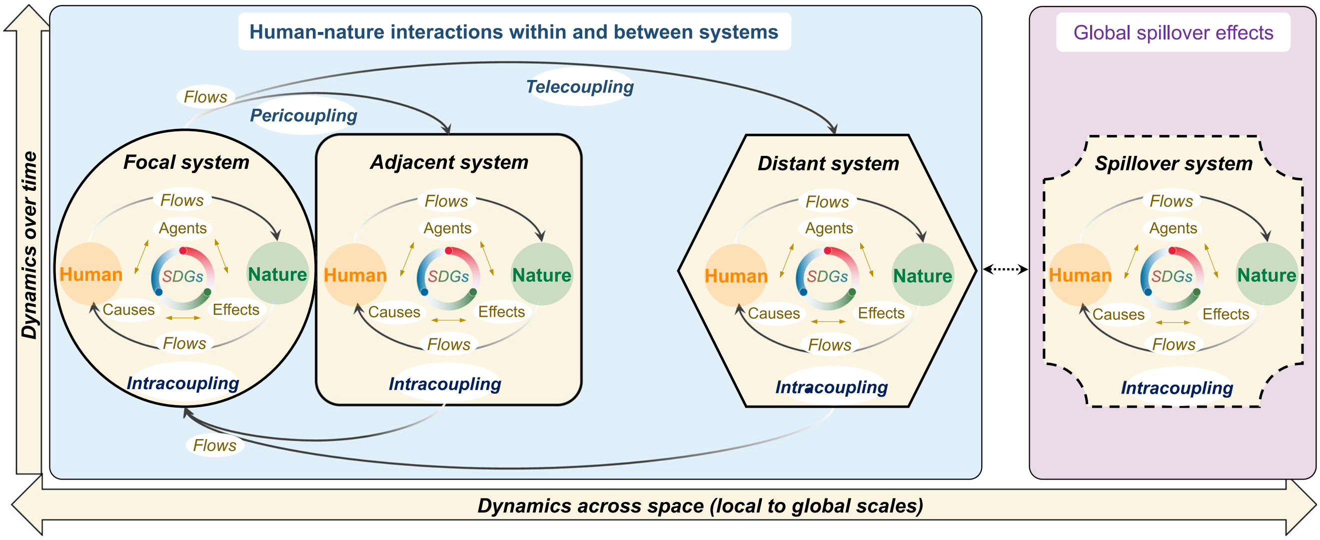

Fig. 1 | Metacoupled human and natural systems and schematic diagram of the metacoupling framework. The solid yellow boxes (left blue panel) represent spatially distinct coupled human and natural systems (e.g., a country, city, or protected area), ranging from the focal system to adjacent and distant systems. Each system comprises human and nature components connected by various flows and generates intra-system human-nature interactions (intracoupling). These distinct systems are also interconnected by transboundary flows (e.g., trade, tourism, and migration) and form feedbacks, creating inter-system human-nature interactions including pericoupling (human-nature interactions between focal and adjacent systems) and telecoupling (human-nature interactions between focal and distant systems). Metacoupling consists of three distinct couplings: intracoupling, pericoupling, and telecoupling. Each system also includes three interrelated components: agents (decision-making entities that facilitate the flows), causes (reasons behind the flows), and effects (consequences of the flows). All these couplings within and between systems can also generate indirect effects globally to spillover systems (dashed box within the right purple panel). Metacoupling occurs across space and evolves over time among interconnected systems (e.g., there may be multiple adjacent, distant, and spillover systems), where any system can simultaneously interact with multiple systems or be influenced by other couplings across space (this diagram represents a simplified spatiotemporal snapshot). From local to global scales, metacoupling formed by these multi-scale human-nature interactions within and between systems, along with other factors, shapes sustainability both within individual systems and globally, represented by the SDGs.

by a combination of research interests, specific context, and data availability[34]. Notably, flows vary across space and time and can be disrupted by global shocks, which have far-reaching implications for addressing sustainability challenges in interconnected systems.

(4) Agents, causes, and effects are three interrelated components of the metacoupling framework. Agents are decision-making entities (e.g., governments, companies, residents) that initiate flows, while causes encompass drivers like policy incentives, market demand, or resource scarcity. Effects represent socioeconomic and environmental consequences, such as income growth or biodiversity loss.

Purpose and value of the metacoupling framework

The metacoupling framework was developed to analyze and address complex, interconnected sustainability challenges that arise from human-nature interactions within and across systems. This innovative framework provides a holistic perspective for understanding sustainability, a unified conceptual foundation for analyzing human-nature interactions, and a standardized approach to identifying research gaps in coupled human and natural systems. The framework has been successfully applied across terrestrial and aquatic systems, addressing a range of social and environmental topics, such as tourism, protected areas, food trade, agriculture, fisheries, and ecosystem services, across local to global scales[28,29,44,47–49]. Here, we illustrate the unique strengths and added values of the metacoupling framework in studying local to global interactions between Wolong Nature Reserve for panda conservation in China (hereafter Wolong) and the rest of the world, along with their sustainability implications[9,31] (Fig. 2). This synthesis of the Wolong case study builds upon previous research[6,8,9,31,50] where the metacoupling framework was developed and applied. The application of this framework requires substantial resources (e.g., expertise, funding, and time) and a suite of methodological tools for tasks such as data collection, systems analysis, and quantifying flows and effects (Fig. 2a, see Section 4 for details). The specific SDG synergy and trade-off results presented here (Fig. 2b) serve as an illustrative example, derived from previous studies in Wolong[29,31]. These studies utilized a rich, long-term dataset in Wolong and empirical methods to quantify SDG interactions (A detailed list of methodological approaches for SDG interaction analysis is provided in Sections 3.1 and 4). The Wolong case highlights several key values of the framework:

(1) It provides a systematic way to advance general analyses by explicitly identifying metacoupled systems across local to global scales, as well as associated flows, agents, causes, and effects. This structured framework can help researchers study complex interactions across systems in a standard way and support diverse research focuses and interests. For instance, Wolong sent 28 pandas to 14 zoos in 12 countries (1998-2017) under international collaboration agreements[31], while also attracting millions of domestic and international tourists. By integrating systems across scales, from Wolong (local) to adjacent regions (regional) and distant countries (global) (Fig. 2a), it enables the identification of key flows including tourism, panda loans, and migration between these systems and their effects. This unified approach allows researchers to examine various components either individually or as interconnected systems for addressing a wide range of research questions.

(2) It enables the spatial explicit differentiation of human-nature interactions into intracoupling (e.g., within Wolong), pericoupling (between Wolong and adjacent regions) and telecoupling (between Wolong and distant countries) (Fig. 2a). This typology offers a unified conceptualization for systematically analyzing the complex human-nature interactions.

Table 1 | Definition of key terms and concepts used in the metacoupling framework

Key terms	Description
Coupled Human and Natural Systems (CHANS)	Coupled human and natural systems are integrated systems in which people interact with natural components[6]. For the metacoupling framework, a coupled system consists of five major components, including subsystems (human and nature), agents, flows, causes, and effects.
Metacoupling	Metacoupling encompasses human-nature interactions (or socioeconomic and environmental interactions) within a coupled human and natural system (intracoupling, such as farming, fishing, and timber harvesting), between adjacent and distant systems (pericoupling and telecoupling, such as trade, migration, tourism, investment, knowledge and technology transfer).
Intracoupling	Human-nature interactions within a coupled human and natural system.
Pericoupling	Human-nature interactions between adjacent coupled human and natural systems.
Telecoupling	Human-nature interactions between distant coupled human and natural systems.
System	A system could be a place such as a country, city, village, or protected area. For intracoupling, the focus is often on one system (focal system). For pericoupling and telecoupling, two or more systems (focal system and adjacent/distant systems) are considered and they can be classified as sending systems and receiving systems, depending on the direction of flows. In addition, there are spillover systems that are affected by or influence human-nature interactions within the focal systems or between the sending and receiving systems.
Flows	Movement of food, energy, people, capital, information, technology, organisms, and materials within a focal system or between adjacent or distant sending and receiving systems as well as with spillover systems.
Agents	Decision-making entities involved in human-nature interactions that drive or inhibit flows such as different stakeholders (e.g., farmers, residents, governors) and animals.
Causes	Drivers of change behind intracoupling, pericoupling, and telecoupling, such as timber harvesting, trade, tourism, and human migration.
Effects	Socioeconomic and environmental consequences caused by intracoupling, pericoupling and telecoupling, such as increased income, deforestation, or carbon emissions.

(3) It allows researchers to have a comprehensive perspective of both socioeconomic and environmental effects, expanding the scope of sustainability research. For instance, Wolong, a flagship giant panda conservation site, attracts global tourism that generates substantial socioeconomic benefits (e.g., economic growth, increased per capita income), while also exacerbating habitat fragmentation and human-wildlife conflicts. These localized effects can have cascading impacts, extending to other panda reserves through collaboration partnerships (Fig. 2a). The metacoupling framework offers a multidimensional perspective to systematically examine both direct and indirect effects across spatial scales.

(4) It connects the SDGs and provides a comprehensive analytical approach to examine SDGs across systems and scales. For example, the framework enables the identification and systematic examination of SDG interactions across systems and scales (Fig. 2b). Locally, tourism introduced mixed positive and negative effects in Wolong. It promoted local economic growth (SDG 8) and generated essential revenue for conservation efforts, but it also brought intensive human activities that increased pressures on local ecosystems (SDG 15)[50]. Regionally, improved living standards in Wolong attract marriage migrants from adjacent counties, creating trade-offs between Wolong's economic development (SDG 8) and gender equality and inequality reduction (SDGs 5 and 10, respectively) in sending counties. Globally, panda loan partnerships between Wolong and overseas zoos enhance international cooperation (SDG 17), demonstrating telecoupled synergies[31]. Moreover, it helps capture indirect spillover effects, such as how collaborative partnerships promote infrastructure development (SDG 9) in other panda reserves. This multi-scale perspective overcomes the critical limitation of conventional SDG analyses which typically focus on individual systems. The metacoupling analysis enables a nuanced understanding of the complex spatiotemporal dynamics (e.g., trade-offs and synergies over space and time) across scales. After incorporating human-nature interactions within a place as well as nearby and far away (e.g., the essence of the metacoupling framework) and their dynamics over time, more useful information was generated to understand the mechanisms behind panda endangerment and to develop more effective and efficient policies. By considering policies inside and outside protected areas, the framework contributed to transforming the habitat of giant pandas, a global conservation icon, from long-term losses to substantial recovery and, ultimately, leading to the panda's removal from the endangered species list[29,31,41,51]. As detailed in the following section, applying the metacoupling framework to SDG analysis has a great potential to expand research perspectives and reveal overlooked sustainability linkages and implications.

The potential of the metacoupling framework in SDG analysis

The metacoupling framework demonstrates transformative potential for advancing SDG analysis from single-system to multi-system perspectives (Fig. 3). The 17 UN SDGs offer a comprehensive and unifying framework for sustainability research across scales and systems. Within the context of the SDGs, we demonstrate the framework's potential through three critical aspects: SDG interactions (interdependencies among goals/targets), SDG progress (advances or setbacks toward goals), and SDG pathways (strategies for achieving goals/targets), aligning with current research priorities, emerging scientific trends, and urgent policy needs[52–54]. The added value of the metacoupling framework as a specific lens for analyzing cross-scale and cross-system SDG interactions, enhancing SDG progress monitoring by revealing spillover effects, and guiding the modeling of transboundary cooperative SDG pathways is illustrated.

Analyzing SDG interactions across systems

SDG interactions arise from the systemic nature of SDGs[55,56], the interdependencies among goals or targets, where progress toward one goal or target influences others[57]. Synergies (positive interactions where progress on one goal advances another) and trade-offs (negative interactions where achievements in one goal undermine another) are two primary forms of these interconnections[58–61]. This often creates dilemmas for government agencies and policymakers when policies or actions risk achieving one goal at the cost of another. While SDG interactions have been widely studied at a level of single systems (global, national, or subnational)[59,62,63] (Fig. 3a), there remains a critical

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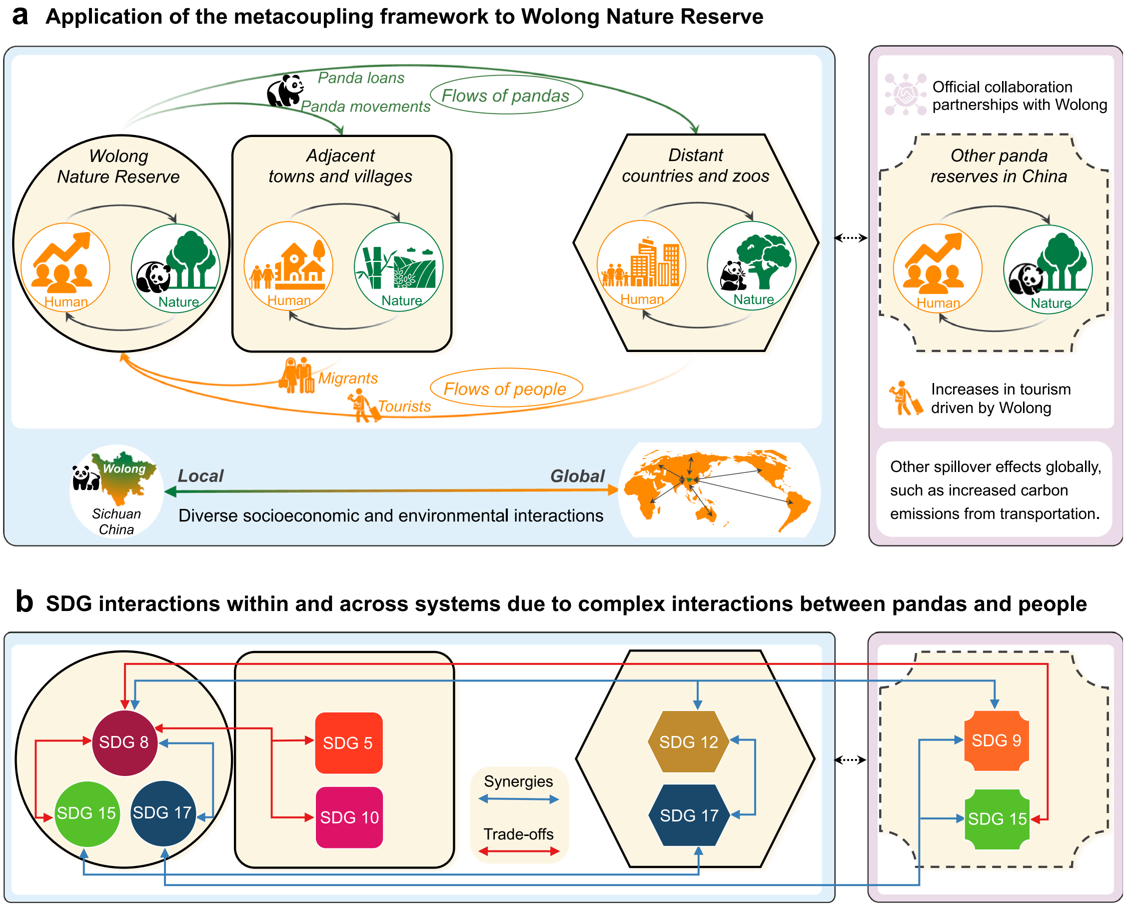

Fig. 2 | Demonstration of Wolong Nature Reserve in southwestern China to illustrate the metacoupling framework and SDG interactions across local to global scales. a Application of the metacoupling framework to Wolong Nature Reserve (Sichuan province, China) for panda conservation[9]. Human-nature interactions within Wolong (intracoupling, e.g., local residents in Wolong influx into panda habitats and forests lead to direct interactions between anthropogenic activities and ecological processes) are intensified by key cross-system interactions, pericoupling (e.g., residents from adjacent towns and villages migrate to Wolong, pandas move to areas next to the reserve), and telecoupling (e.g., international tourism and panda loans). Pandas in Wolong's breeding center are loaned to international zoos through the international panda loan program and some wild pandas may also move beyond reserve boundaries to adjacent areas in search of food and mates and avoid potential risks (flows of pandas). Tourists from around the world travel to Wolong, while some residents from neighboring villages migrate into the reserve through marriage, attracted by better living standards in Wolong (flows of people). Each flow is represented by a directional arrow, with associated causes, agents, and effects not shown for simplicity. Spillover systems (shown here using other panda reserves in China as an example) represent areas globally affected by Wolong's panda loans and tourism activities. These systems experience indirect impacts from Wolong's interactions with other systems, manifesting as strengthened collaboration partnerships with Wolong and increased tourist visitation. **b** SDG synergies and trade-offs occur both within Wolong and across global systems. The complex interactions between pandas and people have diverse sustainability impacts across local to global scales[41], with selected key SDG interrelationships illustrated here[31].

gap in understanding transboundary SDG interactions that span multiple coupled systems across scales[11,64].

The metacoupling framework can help shift SDG interaction analysis from within individual systems to across multiple systems, for instance, pericoupled systems or telecoupled systems (Fig. 3b). Emerging research has leveraged this framework to advance SDG interaction analysis across local and regional boundaries[15,29,31]. One of its key added values is that the framework can help reveal hidden systemic connections that may not be apparent when focusing on a particular system. For instance, Zhao et al.[31] employed the metacoupling framework in studying tourism and panda loans between the globally important Wolong Nature Reserve for panda conservation and the rest of the world. Distinct SDG interactions both within the Wolong and across panda reserve boundaries were identified, for instance, SDG 17 in Wolong indirectly synergizing with SDG 17 in spillover systems by directly enhancing SDG 9 in other panda reserves (Fig. 2b). The framework has also recently been employed to study global transboundary SDG interactions, revealing that high-income countries contribute substantially to over 60% of SDG synergies and trade-offs worldwide[11]. By illuminating these overlooked cross-system linkages from a holistic perspective, the metacoupling framework enables researchers to analyze SDG interactions in a systematic way as well as empowers policymakers to design holistic strategies that mitigate trade-offs and align policies and actions. Insights from SDG interactions are not only essential for a deeper understanding of local to global achievement toward the SDGs (SDG progress) and for guiding strategies to achieve the 2030 Agenda (SDG pathways)[65–68] (Fig. 3b).

A combination of diverse qualitative methods (e.g., expert judgment, narrative modeling, and systematic literature review)[57,69–72] and quantitative approaches (e.g., data-driven statistical modeling, network analysis, and correlation assessment)[59,61,63,73,74] enables a more robust and comprehensive analysis of SDG interactions within the metacoupling framework. Qualitative methods provide critical context-specific insights into relationships between SDGs by systematically integrating available evidence with expert and stakeholder input[75], including the elicitation of Indigenous knowledge[76,77]. These approaches facilitate interdisciplinary dialog and help prioritize policy, enabling the characterization of structural complexity and

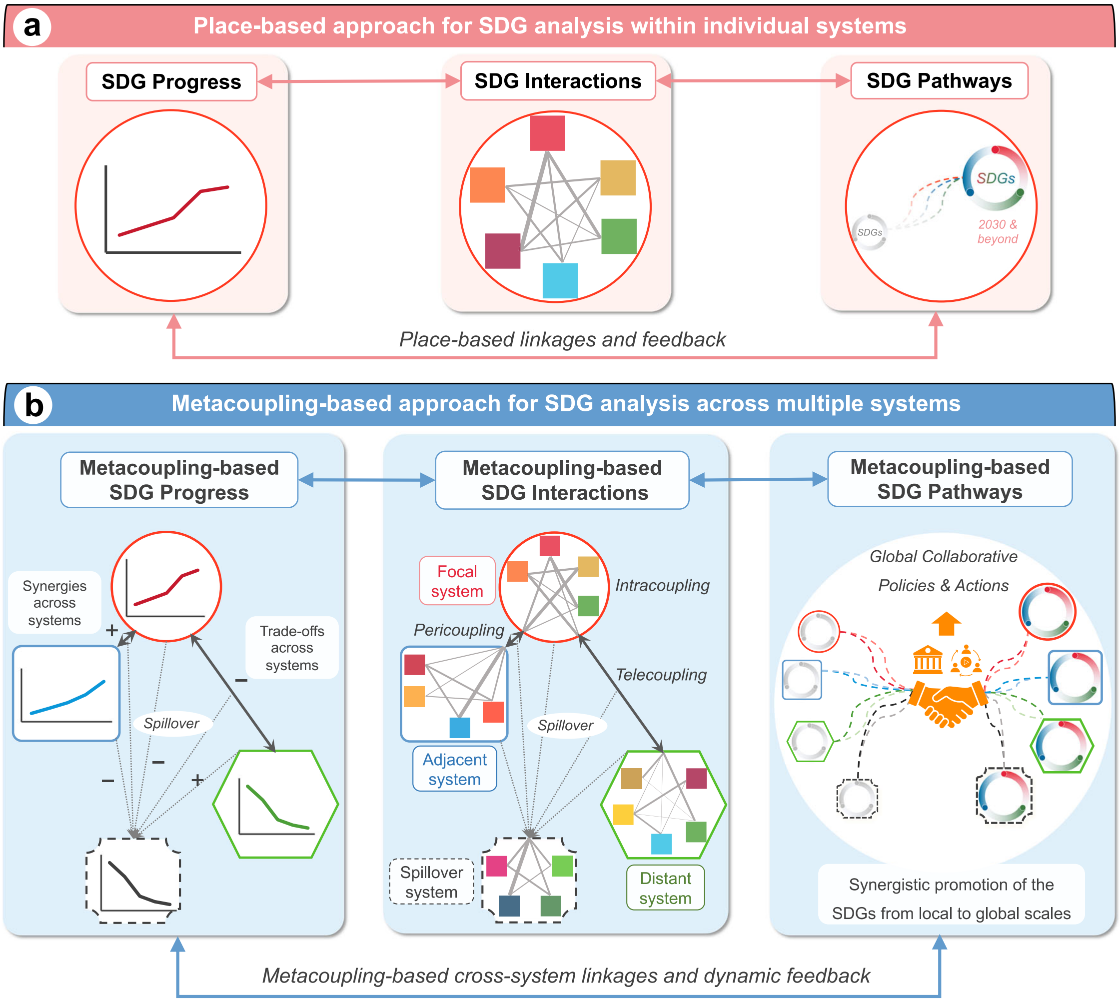

Fig. 3 | The potential of the metacoupling framework for advancing SDG analysis from within individual systems to multiple interconnected systems. **a** Place-based SDG interactions, progress, and pathways within an individual system. SDG interactions (middle) describe the interdependencies among goals (or targets and indicators). SDG progress (left) refers to the advancements towards the goals or targets (solid line). SDG pathways (right) outline strategic policies and interventions (dashed lines) for achieving the 2030 Agenda. **b** Metacoupling-based SDG analysis extends the place-based approach to multiple systems. Metacoupling-based SDG interactions (middle) within the focal system are labeled as 'Intracoupling', which refers to how different goals (or targets) influence each other internally. 'Pericoupling' and 'Telecoupling', indicated by the black bidirectional arrows, refer to cross-system interactions among different goals between the focal system and its adjacent and distant systems, respectively. SDG interactions within and across these systems (solid boxes) could have potential spillover effects on spillover systems (dashed boxes). Metacoupling-based SDG progress (left) illustrates how advancements in one system can positively (synergy) or negatively (trade-off) impact SDG progress in other systems across space and create potential global spillover effects. Metacoupling-based SDG pathways (right) demonstrate diverse approaches through collaborative policies and actions among multiple systems to effectively achieve the 2030 Agenda. The bidirectional arrows (pink & blue) connecting the boxes in (**a**) and (**b**) illustrate place-based and metacoupling-based linkages and feedback among SDG interactions, SDG progress, and SDG pathways, respectively.

directionality of SDG interactions across goals and targets. As demonstrated by Singh et al[69], who developed a hierarchical SDG relationship assessment framework integrating existing knowledge from literature and expert opinions. This approach enables nuanced classification of SDG linkages as co-beneficial, trade-off, or neutral, and further distinguishes whether relationships are prerequisite or optional and context-dependent. Empirical analysis demonstrates that SDG 14 (Life below water) potentially co-benefits every other SDG globally[69]. Notably, six SDGs (1, 2, 11, 13, 15 and 16) are positively linked to every SDG 14 target. Such a qualitative approach is particularly valuable for identifying place-based socio-cultural and governance factors for each SDG while contextualizing pericoupled and telecoupled interactions. For example, sustainable ocean development (SDG 14) in Small Island Development States often depends on international partnerships (SDG 17) for climate change mitigation[78]. However, qualitative methods may be limited in quantifying interaction magnitudes and can introduce subjectivity through cognitive biases or incomplete knowledge. Quantitative methods provide a rigorous, comparable, and data-driven approach to measuring the magnitude of SDG interactions. These methods enable standardized benchmarking of SDG interactions across scales and systems using SDG indicator pairs and time-series data. Correlation analysis, for example, has been widely used to identify synergies and trade-offs at local to global scales[59,61]. However, quantitative methods often ignore contextual socio-cultural factors, may struggle with incomplete or inconsistent SDG indicator data, and risk oversimplification or spurious correlations, as correlation does not imply causality[59]. Therefore, combining quantitative analyses to measure standardized cross-system interaction magnitude with a qualitative understanding of context-specific evidence and systems thinking within the metacoupling framework is essential for comprehensive SDG interaction analysis[55,79,80].

Assessing SDG progress with spillover effects

Conventional SDG progress assessments predominantly rely on indicator-based composite indices, qualitative analyses, and fragmented reports from Voluntary National Review at national or subnational levels[4,81–86]. These approaches provide standardized and comparable metrics for place-based individual countries or cities (Fig. 3a), often enhanced by localized adaptations such as China's and Australia's evidence-based and tailored assessments[4,86]. However, they fail to capture critical cross-system dynamics central to the metacoupling framework. Most existing assessment methods adopt a system-bound perspective to evaluate SDG progress within individual national borders. This often overlooks the many complex interconnections among countries driven by socioeconomic and natural processes, which can generate positive or negative impacts on regional and global sustainability. The lack of robust and systematic methodologies to quantify these transboundary effects and spillovers introduces much uncertainty into SDG progress assessments. More critically, this oversight undermines the "Leave No One Behind" principle, as root causes of inequality and inequity, such as geopolitical power imbalances, the marginalization of vulnerable communities, and extractive transnational resource hierarchies, often remain inadequately addressed[10,45,87,88].

The metacoupling framework enables a holistic assessment of SDG progress by accounting for the positive or negative effects of intracoupling, pericoupling, and telecoupling across systems (Fig. 3b). For instance, it allows for systematic assessment of how SDG progress at the national level is influenced by distinct types of couplings, defined by geographical trade distances. Using this framework, Xu et al[15] quantified the temporal dynamics of intracoupling (no international trade), pericoupling (adjacent trade), and telecoupling (distant trade), and their impacts on SDG target scores, and revealed that distant trade was more beneficial for achieving SDG targets in developed countries than adjacent trade. Moreover, a key innovative aspect of the metacoupling framework is its capacity to identify and analyze spillover effects[45,89]. Recent annual Sustainable Development Reports have included a Spillover Index to evaluate how a country's actions affect other countries' abilities to achieve the SDGs[90]. The metacoupling framework can further quantify spillover effects through metrics such as embodied carbon in trade or resource footprints, thus revealing how developed countries may generate negative socioeconomic and environmental spillovers, including through unsustainable trade and supply chains[15,44,47]. By integrating these spillovers into SDG Index calculations, the framework redefines "progress" as a net outcome of interconnected gains and losses, helping to translate the 2030 Agenda's promise to "Leave No One Behind" into measurable and equitable action[89].

Modeling SDG pathways in a metacoupled lens

SDG pathways refer to strategic routes, integrated actions, and transformative processes required to achieve the SDGs[91,92]. Diverse policy portfolios and interventions (e.g., natural climate solutions) profoundly influence sustainability outcomes across systems and scales[66,93,94], resulting in divergent SDG pathways at local, national, and global scales[95]. Current SDG pathway modeling predominantly adopts a place-based and single-system perspective, focusing on specific nations or cities (Fig. 3a). For instance, country-specific models for Australia[66] and China[94] have tailored strategies and policies to their unique development contexts. However, these scenario-based models often overlook cross-system effects and global spillovers, which can amplify local projection uncertainties and exacerbate transnational inequalities. Moreover, quantitative synthesis and comparison of pathways across countries or cities remain challenging due to variations in modeling methods and assumptions for different goals and targets within individual systems across scales[96–101]. This analytical gap hinders global sustainability coordination, limiting the capacity to identify and maximize transnational SDG synergies while mitigating cross-system trade-offs.

The metacoupling framework offers transformative potential for SDG pathway development by systematically modeling cross-sectoral and cross-system collaboration partnerships to promote synergies (Fig. 3b). As it is likely that no country will fully achieve the SDGs by 2030[102,103] and global shocks continue to emerge and intensify, the framework provides a structured approach to optimize limited time and resources. Metacoupling-based pathways aligns with the "Leave No One behind" principle by explicitly addressing multiple systems and their SDGs. Researchers can use scenario analysis and quantitative modeling approaches[66,96,98,99] within the metacoupling framework to develop transboundary management strategies and collaborative pathways for overall sustainable development. For example, it is essential to consider intercity interactions and spillover impacts in city-level SDG pathways modeling. Actions within a city generate excessive resource exploitation and environmental pollution in adjacent and distant rural areas that provide many essential resources. Metacoupling-informed SDG pathway modeling not only accounts for human-nature interactions within a city but also enables cost-effective policy learning between cities while mitigating the displacement of sustainability burdens across urban and rural systems[100,104].

The operationalization of the metacoupling framework in sustainability research

Operationalizing the metacoupling framework for SDG analysis requires effective guidelines and a suite of tools (Supplementary Table 1), including those applied in metacoupling and SDG research as discussed in Sections 3.1–3.3. While extensive research has demonstrated that cross-system interactions can critically shape social and environmental outcomes across local to global scales[12,26,37,105–107], most studies do not explicitly address the SDGs or provide systematic operationalization guidelines and steps. To advance its application for SDG analysis and generate scientific insights for actionable solutions, we propose six interrelated steps that integrate diverse methods to systematically operationalize the metacoupling framework[9,89], demonstrated through a case of the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) in China (Fig. 4). The following steps outline a general logical progression for applying the metacoupling framework. However, this process is not rigidly linear but inherently iterative and interrelated. Steps may be conducted out of order, revisited cyclically as understanding deepens, or occur concurrently, depending on the specific research context and focus. For instance, a project may launch from a local government policy mandate targeting specific places (Step 2) that subsequently informs the formulation of its research goals (Step 1); Stakeholder engagement (Step 6) could begin much earlier and continues throughout, fundamentally reshaping prior steps. The detailed steps are described below:

Step 1. Setting the SDG research goals: SDG research goals may be motivated by unique priorities and challenges in achieving one or more goals and targets of the 17 SDGs within a regional context (Fig. 4a). The aim is to generate holistic scientific evidence to inform and advance sustainable development and conservation initiatives. In China's development blueprint, the development of the GBA is a key strategic priority, focusing on deeper internal cooperation among mainland cities, Hong Kong, and Macao, as well as stronger international connections. As such, both internal and cross-system interactions are crucial for achieving the GBA's sustainable development. For the GBA demonstration, the main SDG research objective is to understand SDG interactions between the GBA and its adjacent and distant systems and implications for local to global SDG progress and SDG pathways (Fig. 4b). The framework is flexible, allowing for several analytical entry points such as system-based or agent-based analyses and enabling researchers to focus on specific components (e.g., flows

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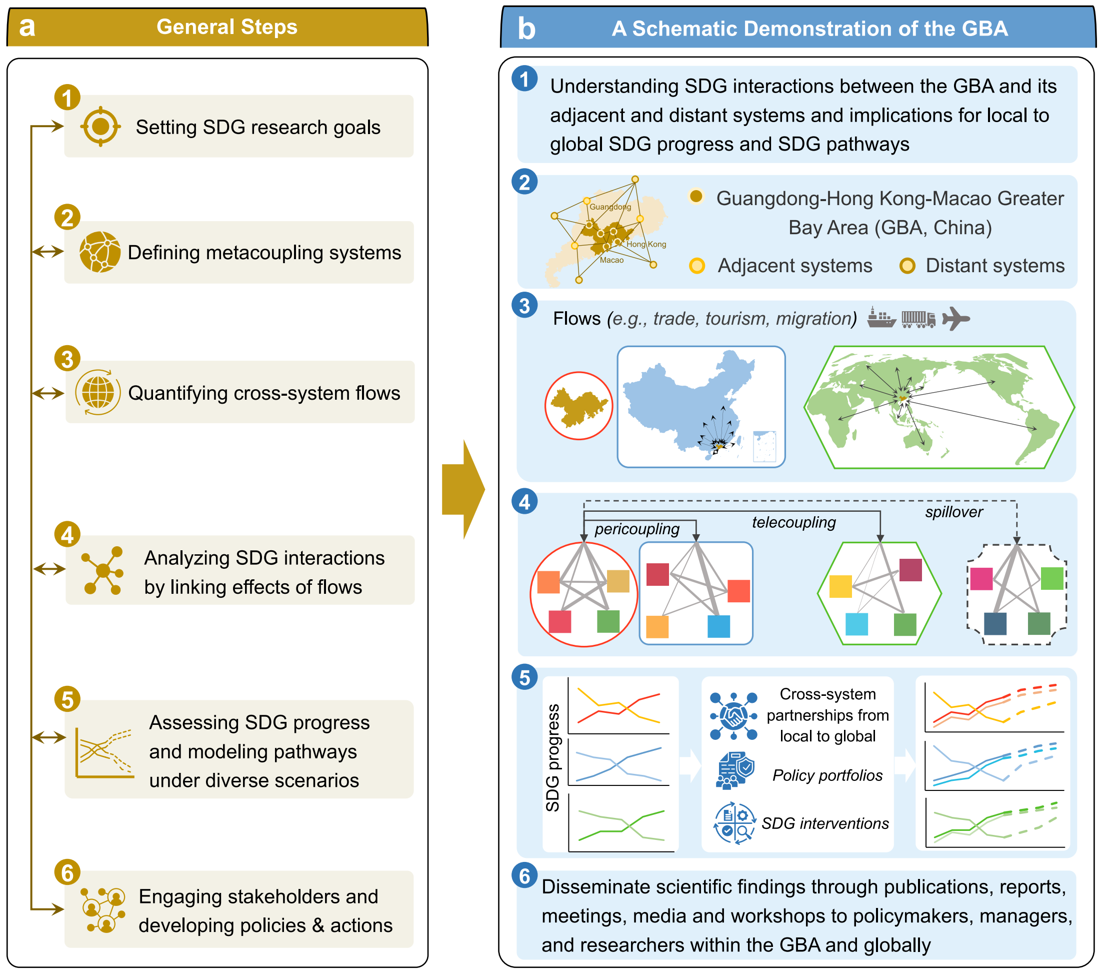

Fig. 4 | General steps for operationalizing the metacoupling framework in SDG research, illustrated with a schematic demonstration of the Greater Bay Area (GBA). a six interrelated steps of applying the metacoupling framework for understanding cross-scale and cross-system interactions to generate scientific evidence for developing effective and synergistic policies and actions. Bidirectional arrows linking Step 6 to all other steps indicate that the process is not strictly sequential and that each step can have important effects on earlier ones. Stakeholder engagement is a continuous process that could inform and calibrate the research from inception through implementation. These simplified steps are grounded in numerous successful case studies[11,28,31,44,47,49] that have utilized the metacoupling framework. **b** a schematic diagram of the GBA following the six steps to explore the potential of the metacoupling framework in analyzing cross-system SDGs from local to global scales. The GBA comprises Hong Kong and Macao, and nine cities in Guangdong Province. The identification of adjacent and distant systems in relation to the focal GBA system is based on research interests and contexts and geographic proximity (Steps 1 & 2). Multiscale flows connect the GBA internally and with other systems globally (Step 3). Socioeconomic and environmental effects of flows produce cross-system SDG interactions and spillover effects (Step 4). Implications of metacoupling-based SDG interactions further support integrated SDG progress assessment and collaborative pathway development to promote the SDGs worldwide (Step 5). These insights can inform multi-stakeholder engagement, fostering synergistic sustainable development planning in the GBA and beyond (Step 6).

or effects) or specific SDGs (e.g., trade-offs between SDG 8 and SDG 14) for detailed analysis.

Step 2. Defining metacoupling systems: This involves identifying the focal, adjacent, and distant systems, which act as either sending or receiving systems for various flows and underpin cross-scale interactions. The focal system refers to the primary area of the study, which could be a nation, region, or city (Fig. 4a). The GBA, located in southern China, encompasses nine cities in Guangdong Province, along with Hong Kong and Macao (Fig. 4b). This region exemplifies a dynamic and interconnected urban system, marked by advanced socioeconomic structure and complex land-ocean ecosystems. Within this focal system, intensive human-nature interactions intersect with intercity exchanges and global flows[108,109], necessitating integrated systems analysis frameworks to effectively promote the SDGs[110]. As a globally important hub bridging Chinese and international Bay Area systems, the GBA facilitates exchanges between adjacent Chinese cities and distant global regions, creating a multiscale network of flows (e.g., trade, tourism, and finance). This unique integration of local, regional, and global interdependencies positions the GBA as an ideal demonstration site for the metacoupling framework, offering nuanced insights into how coupled human-natural systems interact across scales.

Step 3. Quantifying cross-system flows: Identifying and quantifying patterns and trends of flows of materials, organisms, people, and capital are crucial for describing interactions among systems (Fig. 4a). The focal system GBA is intricately linked with both adjacent and distant systems through various types of flows, including physical flows (e.g., water, food, energy, humans), non-material flows (e.g., social services, knowledge) and virtual flows (e.g., environmental footprints and risks), facilitated by different modes like boats, vehicles, and airplanes (Fig. 4b). Methods such as statistical data-based approaches, data crowdsourcing approaches, and process-based modeling are commonly used to quantify physical and non-material flows[34]. Input-output models, life cycle assessments, and footprint methods are often utilized to quantify virtual flows such as the carbon footprint of consumption and the virtual water embodied in trade[14,15]. These analyses rely on a range of datasets, which could be sourced from publicly available national and subnational statistical data and novel datasets from Automatic Identification System, remote sensing, the Internet of Things, and social media. For instance, the Food and Agriculture Organization (FAO) Corporate Statistical Database, the World Trade Organization (WTO), and the United Nations Commodity Trade Statistics Database can help quantify trade flows in agricultural products and commodity trade flows. Global tourism and migration statistics can inform human flow analysis. Capital investments among cities within the GBA can be measured using public and company statistical datasets[109]. The timing, modes, and distances of these flows can be further explored based on specific research questions. Other framework components, such as agents (e.g., companies, policymakers, farmers), causes (e.g., population growth, resource constraints), and effects (e.g., biodiversity loss, income disparities), can be qualitatively summarized through expert-guided processes, interviews, and surveys, enabling rigorous analysis of SDG outcomes.

Step 4. Analyzing SDG interactions linking effects of flows: It is important to link the quantified flows to specific SDG targets and indicators (Fig. 4a). SDG interactions that occur both within its boundaries (intracoupling) and across adjacent (pericoupling) and distant (telecoupling) systems constitute metacoupling-based SDG interactions for the GBA (Fig. 4b). For instance, collaborative developments between Hong Kong and other GBA cities exhibit intracoupling: Hong Kong's reliance on food and water from Guangdong drives land-use changes in the region and increases income for local farmers, linking SDGs 2, 8, and 15. Additionally, Hong Kong's re-exports of goods to distant international markets drive urban development and manufacturing growth in the GBA and adjacent Mainland regions. This connects the GBA's SDGs with adjacent and distant areas' SDGs 8, 11, and 12. These intra- and inter-regional interactions also embed various cross-regional carbon emissions, leading to spillover effects on other regions and countries, with implications for SDG 13 globally. To analyze these interactions, first, key cross-system interactions aligned with specific SDGs can be identified through existing knowledge from literature and expert opinions[69]. Then, quantitative techniques, such as correlation analysis, network analytics tools and agent-based modeling[9,60,61], can be used to effectively quantify interaction strength and trends across intracoupling, pericoupling, and telecoupling. By integrating qualitative insights and quantitative rigor, this approach provides a comprehensive understanding of SDG interactions from local to global scales.

Step 5. Integrated SDG progress assessment and SDG pathways modeling: In this step, scientific evidence from SDG interaction analysis is leveraged to enhance understanding and promote sustainable development across multiple systems (Fig. 4a):

(1) To systematically assess SDG progress, researchers can use established indicator-based methodologies and ongoing initiatives, such as the SDG Index and dashboards[2] and relevant case studies[4,83,100]. These approaches provide a foundation for evaluating GBA's progress toward the SDGs over time and across different areas within GBA. Incorporating the insights from cross-system interactions, similar to the Spillover Index in the Sustainable Development Reports[90], allows for a more nuanced understanding of how inter-system dynamics affect overall SDG progress (Fig. 4b). Robust data collection is key, which can be supported by the development of a big data center and platforms for international innovation, as outlined in the GBA's Development Plan[111]. In addition, a wealth of accessible national and international open data sources, such as those from the World Bank and national and subnational statistical yearbooks, as well as emerging geospatial information from satellite remote sensing, social media, and the Internet of Things can further enrich the data landscape.

(2) To model effective SDG pathways, researchers should develop portfolios of policies and interventions maximizing cross-system synergies while managing trade-offs, considering the diverse institutional and political contexts of various regions. Scenario-based models and frameworks integrating metacoupling can be used to identify and assess viable pathways for advancing SDG progress, especially for lagging goals or targets across systems. One potential approach is to adapt existing methods, such as the Shared Socio-economic Pathways and the Integrated Sustainable Development Goals (iSDG) model[66,94], and create a subnational level model for the GBA. By incorporating cross-system interactions, feedback loops and cascading effects from global shocks such as climate extremes and US-China trade war, the integrated model can extend the analysis beyond a single system to encompass multiple systems, thereby providing a comprehensive assessment of SDG progress under various pathway scenarios (Fig. 4b).

Step 6: Stakeholder engagement and SDG policies and actions development: In this step, it is important to integrate scientific evidence into policymaking and support the implementation of actions aimed at promoting the SDGs across multiple systems (Fig. 4a). This underscores the utility of the metacoupling framework as a valuable tool for sustainable development planning, offering a structured approach to understanding and addressing the interconnections and interactions between systems. By leveraging integrated knowledge, engaging diverse stakeholders, and implementing coordinated strategies, decision-makers can navigate trade-offs and align compatible objectives. It is essential to disseminate the findings to stakeholders, including policymakers, managers, and researchers, through various channels (Fig. 4b). More importantly, the proposed six interrelated steps are highly iterative, with dynamic feedback between them, meaning a change in one can create cascading effects on other steps (Fig. 4a). Stakeholder engagement is not a single event but a continuous activity that could begin at the project's inception. Early and ongoing input from stakeholders is essential for co-defining research objectives, refining questions, and ensuring the work remains relevant. This iterative cycle, where steps may be revisited based on new information or stakeholder feedback, ensures the feasibility and effectiveness of translating metacoupling analysis into actionable policies for sustainable development[112].

Collectively, these steps demonstrate the feasibility of operationalizing the metacoupling framework as a practical tool for researchers to analyze cross-system interactions. This framework effectively addresses policy concerns related to practical sustainability drivers and flows and has implications for shifting local and global sustainability governance. Figure 5 summarizes literature that demonstrates the potential of the metacoupling framework for analyzing cross-system SDG interactions across diverse cases, drivers, and flows in future research. The framework provides a structured approach to deconstruct complex interactions between SDG targets by identifying key agents, flows, causes, and effects across local, regional, and global scales. This diagnostic process generates critical, actionable knowledge by expanding existing analyses to address the SDGs within an integrated metacoupling context. For example, applying the framework to analyze the cross-country impacts of war on SDGs 2 and 15 can guide policymakers in preventing farmers in biodiversity hotspots far from the conflict (e.g., in Brazil, Mesoamerica, and Southeast Asia) from rapidly expanding agricultural land unsustainably[24]. Instead, it can steer interventions towards sustainable practices, thereby advancing the Post-2020 Global Biodiversity Framework by incorporating the overlooked distal biodiversity impacts of

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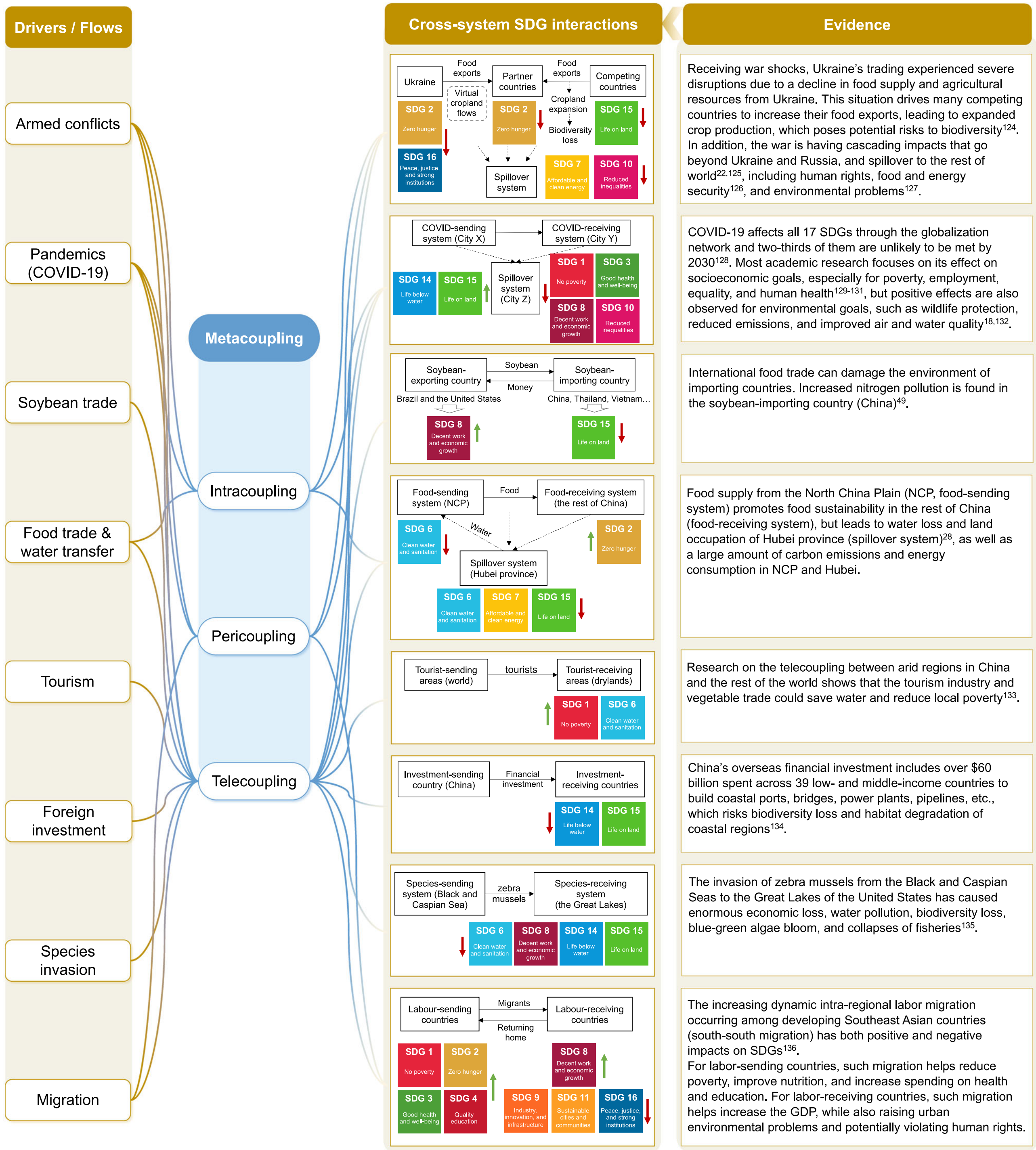

Fig. 5 | The potential of the metacoupling framework in analyzing cross-system SDG interactions in possible cases with various drivers and flows. Diverse drivers and flows between systems (e.g., countries, regions, and cities), such as armed conflicts, pandemics, and commodity trade, can produce both positive (green arrows) and negative (red arrows) effects on SDGs across local to global scales. The metacoupling framework provides a structured approach to deconstruct these complex cross-system SDG interactions by integrating intracoupling, pericoupling, and telecoupling perspectives, thereby extending existing analyses to yield critical, actionable insights. The SDGs shown are selective for clarity, based on available evidence from existing literatures. Many real-world cross-system SDG interactions are more extensive than can be fully depicted or are currently understudied[116,123–134].

war into national plans. In another example, a metacoupling analysis of the global soybean trade can reveal unexpected environmental damage (e.g., soil pollution linked to SDG 15) in importing countries, driven by a shift in cropping patterns[49]. This knowledge facilitates policymakers in rethinking and redistribute environmental responsibilities equitably among global consumers, producers, and traders in a systematical and equitable way.

Applying the metacoupling framework generates knowledge that helps shift governance from a traditional place-based model toward a metacoupling-based approach. This integrated approach explicitly accounts for cross-system interactions, along with their associated agents, causes, and effects. Such a shift can help international institutions like the UN, FAO, and WTO catalyze effective transboundary management strategies and fostering global cooperation initiatives.

Major global sustainability initiatives, such as the Paris Agreement, the Carbon Neutrality Action, and the post-2020 biodiversity framework, require cooperation among nations with diverse socioeconomic backgrounds. The metacoupling framework helps coordinate different policy measures within focal systems as well as across adjacent and distant systems[89]. By evaluating the effects of various policies on SDGs in a specific system as well as in adjacent and distant systems (e.g., the Wolong reserve case to save pandas), the framework can help enhance positive effects, reduce negative impacts, and promote SDGs across scales[89].

Challenges and future directions

The comprehensive scope and methodological flexibility of the metacoupling framework create opportunities to integrate previously siloed disciplinary or place-based research into a holistic understanding of cross-system interactions. However, there are also framework operationalization hurdles and persistent research challenges that require further attention and concerted efforts, including insufficient data availability and a lack of standardized analytical tools; high demands for interdisciplinary expertise and resources; the difficulties and monotony involved in tracking flows across scales; the complexity and variability associated with unexpected impacts of global shocks across systems; the ambiguity in developing sustainable pathway strategies; and a shortage of actionable evidence linking scientific research to policy in SDG implementation and governance. To address these challenges, the following key strategies and research directions informed by recent SDG studies and the GBA demonstration are proposed:

Enhancing data availability and standardized analytical tools

The framework's effectiveness is constrained by fragmented and inaccessible multi-scale, multi-disciplinary data. Critical transboundary flow data (e.g., tourism, migration, pollution) needed for SDG interaction analysis are often unavailable at subnational levels, especially in developing regions, restricting spatial resolution and analytical precision. In addition, no unified toolkit exists for metacoupling analysis, forcing researchers to rely on disparate models and software from different disciplines. Integrating data from various sources for SDG analysis is challenging without a common analytical platform, which may hinder comparative studies and cross-disciplinary collaboration. To address these barriers, establishing a spatiotemporal data center to track cross-system flows and leveraging emerging datasets such as satellite-derived Big Earth Data and social media analytics would be a viable solution. Developing robust and integrated modeling platforms is imperative to standardize and integrate analytical methodologies and facilitate cross-disciplinary data synthesis in metacoupling and the SDGs.

Fostering interdisciplinary collaborative research networks worldwide

The comprehensive nature of the framework necessitates collaboration among ecologists, geographers, economists, policymakers, data scientists, and experts from many other disciplines. Such interdisciplinary efforts demand substantial time investments and financial resources that often exceed available funding. Sustainable funding and institutional support are critical but remain insufficient, particularly for large-scale transboundary research initiatives. To foster the framework's future operationalization and widespread application, substantial investments in interdisciplinary training programs are needed to cultivate researchers capable of bridging disciplinary gaps between natural and social sciences. Moreover, establishing global collaborative research networks across countries will further advance cross-system SDG research.

Quantifying cross-scale and cross-system interlinkages

This involves identifying and mapping extensive interlinkages that influence the socioeconomic SDGs through novel channels, moving beyond the traditional focus on environmental SDG analyses of trade flows[15,47]. Promising avenues for future research include quantifying cross-system links such as capital circulation, human migration, and infrastructure-related traffic flows, especially at finer spatial scales (e.g., intra-national disparities or urban-rural gradients). Emerging data streams from remote sensing, social media, and the Internet of Things networks offer granular insights for tracking these interactions. Developing user-friendly tools (e.g., flow tracers and visualization tools) leveraging innovative technologies such as artificial intelligence and digital twins[113–115] can further advance the understanding of metacoupling processes and dynamics and support interdisciplinary researchers.

Investigating metacoupled cascading and spillover effects

Increasingly frequent and unexpected global shocks, particularly climate extremes, armed conflicts, pandemics, and economic crises, generate cascading and spillover effects that propagate across interconnected systems, creating cumulative and compounded risks over time. It is estimated that two-thirds of the SDGs are unlikely to be met due to the depressed economic market and disrupted globalization[116]. Future research should prioritize quantifying the patterns, magnitude, and spatial-temporal propagation of these effects within the metacoupling framework. This will enhance systematic mapping and analysis, providing actionable evidence to assess the resilience and vulnerability of global sustainability.

Modeling metacoupled sustainable development pathways

Integrative scenario analyses should account for cross-system interlinkages and disruptors[66,94] within the metacoupling framework. Integrating global commitments such as the Paris Climate Agreement and the Kunming-Montreal Biodiversity Framework into the metacoupled pathways can enhance policy coherence and reveal hidden feedback loops between climate mitigation, biodiversity conservation, and sustainable development priorities. Metacoupling effects on spatial justice can be considered under different scenarios that integrate existing Shared Socioeconomic Pathways to identify governance interventions that reduce spatial inequity and inequalities. To ensure rigor, metacoupled pathway modeling should prioritize consistency and comparability across systems and scenarios, enabling policymakers to benchmark progress and avoid fragmented strategies.

Generating actionable evidence through grounded metacoupling applications

Future research leveraging the metacoupling framework should prioritize actionable evidence for SDG implementation and governance, delivering concrete guidance for policymakers and planning bodies at local and national levels. Studies can adopt participatory approaches engaging governments, communities, and private sectors to co-design context-specific strategies and tools[117]. Integrating metacoupling insights into national statistical systems will refine SDG monitoring by capturing cross-boundary flows and spillovers that traditional metrics miss. Grounding analyses in real-world policy challenges will advance adaptive governance across systems and ensure SDG efforts align with the principle of "Leaving No One Behind".

In this paper, we provide an overview of the metacoupling framework, including its foundational concepts, analytical structure, functions, and practical demonstrations. We highlight the framework's potential and operationalization as a systematic lens for advancing sustainability research and SDG analysis. As researchers and policymakers seek concrete guidance for a more comprehensive SDG analysis and effective actions to promote SDG achievement, this work has profound theoretical and practical implications for future sustainability research and policy making. Much of the existing literature has been criticized for relying on broad frameworks and large-scale international policy planning that lack specificity in addressing the complex nature of interconnected sustainable development challenges[118–122]. Future sustainability research could adopt the metacoupling framework as an integrative platform. This will leverage big data, AI, expert knowledge, and multi-stakeholder engagement to generate actionable, policy-oriented analyses, ensuring effective and scalable outcomes for sustainable development across local to global scales.

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Author contributions
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Correspondence and requests for materials should be addressed to Zhenci Xu or Jianguo Liu.

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