Article title: **Meta-CHANS: Linking Metacommunity Ecology with Coupled Human and Nature Systems to Foster Conservation Management**

Type of article: **Perspective**

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Statement of authorship:

ZH and ML led the conceptual basis and wrote the first draft of the manuscript. ZH created figures with input from all authors. All authors contributed substantially to developing the ideas for the manuscript in a workshop and to revising the manuscript.

Data accessibility statement: Data sharing is not applicable to this article as no new data were created in this study.

Short running title: A new spatial framework for conservation

Keywords: metacommunity ecology; Coupled Human and Natural Systems; biodiversity conservation; socio-ecological systems; structured decision-making; spatial ecology; nature's contributions to people; metacommunity processes

Number of words in the abstract: 158

Number of words in the main text: 4634

Number of words in each text box: 613; 199

Number of references: 59

Number of figures: 5

Number of tables: 1

Number of text boxes: 2

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Abstract

Spatial processes shape both ecological dynamics and human decision-making. Here, we propose a unifying framework – Meta-CHANS – that integrates metacommunity ecology into the concept of Coupled Human And Natural Systems (CHANS). We highlight how recent theoretical and methodological advances, especially in species distribution modeling and process inference, allow the identification of dominant metacommunity dynamics and their consequences for biodiversity and ecosystem function. We discuss how coupling between human and natural systems across spatial scales might influence ecosystem processes and properties, and how this can inform a decision-making process using elements of structured decision-making. We demonstrate the applicability of our Meta-CHANS framework through testable hypotheses and predictions, illustrated with an empirical case study and further conceptual examples from river management, urban green space planning, and invasive species management. We illustrate how local- and landscape-level intervention alternatives might lead to different outcomes in terms of metacommunity processes, and highlight the potential of Meta-CHANS to bridge ecological theory and applied environmental decision-making.

Introduction

For millennia, humans have been part of natural systems, but we have now reached a point where virtually no part of Earth is free of human influence. Over the past decades, conservation thinking has shifted from the concept of "nature for itself" through "nature despite people" and "nature for people" to the current view of "people and nature", which emphasizes the reciprocal links between humans and natural systems (Mace 2014). This perspective is addressed explicitly in the concept of Coupled Human And Natural Systems (CHANS; Liu *et al.* 2007, 2021), which builds on the idea that both ecological and socio-economic systems are complex with coupling effects between them. The two systems share many characteristics, including nonlinear relationships, adaptive components, feedback loops, and multiscale structures in space and time, and have multiple connections and interdependencies. This complexity is a challenge for developing conceptual frameworks that can efficiently address the links and feedback routes between the two systems.

A key feature of both socio-economic and ecological processes and dynamics is their strong spatial components. Local systems are influenced by the regional context, while ecological processes and management decisions at local scales can also have regional consequences. Meta-ecology (Schiesari *et al.* 2019) - a collective term encompassing metapopulation (Hanski 1998), metacommunity (Leibold *et al.* 2004) and meta-ecosystem ecology (Loreau *et al.* 2003) - explicitly accounts for spatial dynamics and landscape structure (Cid *et al.* 2022; Little *et al.* 2022; Schiesari *et al.* 2019). We propose that integrating meta-ecology (Schiesari *et al.* 2019) with the CHANS concept (Liu *et al.* 2007, 2021) therefore provides a useful framework for a better understanding of the joint human and ecological spatial components, which can support more realistic and effective conservation management decisions.

For this integration into the CHANS concept, we here focus on metacommunity ecology because it has rapidly developed into a sufficiently mature field that encompasses all the major factors underlying dynamics of ecological communities across spatial scales. Depending on the context, this may also involve metapopulations (when single species are of interest or species of interest do not interact with each other) and/or meta-ecosystems (when the flux of materials and energy in a landscape are of interest). Metacommunity ecology incorporates key aspects of metapopulation ecology, especially when evolutionary processes and landscape genetic structure are included, such as in the evolving metacommunity framework (Urban *et al.* 2008). In addition, it has important implications for meta-ecosystem dynamics through the structure, diversity, and evenness of metacommunities.

Below, we first outline fundamental features of socio-economic dynamics in decision-making and the CHANS concept in a simplified form, highlighting its key elements most relevant for biodiversity conservation. We then describe the fundamentals and multi-scale dynamics of metacommunity ecology and how these two perspectives can be integrated within a CHANS framework, resulting in a new framework that we call Meta-CHANS. We illustrate the applicability of this framework with an empirical case study and three conceptual examples of applied environmental issues that have a clearcut spatial component: river management, urban green space planning, and invasive species management. Using these examples, we highlight how shifting the scale (from local to regional) in management alternatives can modify spatial processes, with consequences for ecosystem properties and nature's contributions to people (NCP).

Structured decision-making and the concept of Coupled Human And Natural Systems (CHANS)

At the practical level of environmental management, we draw upon the structured decision-making framework developed by Gregory *et al.* (2012), building on the work of Clemen & Reilly (1999). This framework integrates three key components: a) science-based approaches, b) consensus-based societal procedures, and c) technocratic tools, e.g. economic evaluation based on multi-criteria approaches, typically focused on utility. Here, utility refers to how different outcomes, such as various NCP or ecosystem services (e.g., habitat creation and maintenance, regulation of water quality, learning and inspiration, or supporting identity) are valued and weighed against each other when evaluating management alternatives (Langhans *et al.* 2019). The structured decision-making framework emphasizes the balanced use of these three components using sequential steps (depicted in **Figure 1a**) with useful decision-making as its final goal. We argue that such an approach can be especially useful for practical decision-making when there is sufficient understanding of many of the specific issues involved, which is typically the case in issues occurring at local or smaller regional scales.

However, CHANS can also involve more general policy issues at larger spatial, socio-economic, and temporal scales (Díaz *et al.* 2018). Here, we incorporated elements from the ecosystem services literature (Daily *et al.* 2009; Mandle *et al.* 2021; Xu & Peng 2022) and political theory (Ostrom 2009; **Figure 1b**).

There is a parallel structure on the human side of CHANS and metacommunity dynamics, as more immediate, context-dependent decisions take place at local scales and interact with broader policy components at regional to international levels. Here, we aim to provide tools to support pragmatic decision-making, especially at the local scale, e.g. managing a single lake or a forest lot in a nature reserve corresponding to a local community in ecological terms. However, just as local communities are shaped by regional processes, local human decisions are also affected by broader policy and political context. This can also feed back to affect local decision-making (albeit more slowly; **Figure 1c**). This interaction is mediated via a two-fold understanding of NCP and nature-based solutions (Díaz *et al.* 2018; IPBES 2019; Pascual *et al.* 2017) – amended from “ecosystem services” in earlier literature). On one hand, the NCP framework defines a general value system for ecosystems (**Figure 1b**), which affects the ways societies develop institutions (both private and governmental) that in turn influence policies affecting the regulation and legal context of decision-making. On the other hand, NCP have a central role in structured decision-making as part of evaluating trade-offs (**Figure 1c**), interacting with other human drivers, such as economic or socio-cultural factors, that influence the perceived utility or substitutability of different NCP outcomes in pragmatic decision-making (see e.g. Langhans *et al.* 2019).

What is metacommunity ecology, and how does it work?

Community dynamics that determine the composition of local biotic assemblages in a landscape involve five primary processes: optimizing abiotic selection, density-dependent biotic selection, dispersal, drift (stochasticity), and speciation (novelty) (Thompson *et al.* 2020; Vellend 2010) (**Figure 2b**). The first of these five processes is density-independent selection, often involving responses to local abiotic conditions in which species have intrinsic growth rates determined primarily by environmental factors that are assumed to be independent of the biota (e.g. temperature, salinity, incoming light). The second process is density-dependent selection in which different species are favored depending on the presence/abundance of other species and feedback among their interactions. This can involve direct interactions among species or indirect ones (involving e.g. resource competition, predation, mutualism). The third process is dispersal or the movement of individuals among localities. If dispersal is limited, some localities will not be occupied by all appropriate species, even though they might be favored there, because they cannot colonize or have not yet been able to do so. In contrast, if dispersal is in excess, some localities may be occupied by species that would otherwise be selected against, because they immigrate at sufficient rates to maintain sink populations due to dispersal from source populations where they are successful. The fourth primary process is stochasticity which accounts for a variety of effects that cannot be related to the processes above, including disturbances due to outside forces and drift that accounts for the stochastic nature of demographic events (e.g. births, deaths) or colonization events that can determine the order of arrival of different species. The fifth and final process is 'novelty'. Vellend (2010) originally conceived of this as primarily involving speciation, but it may make sense to include any process that changes the nature of the regional biota, such as long-distance colonization, perhaps due to human activities or shifts in regional climate. To date, novelty has received much less attention in metacommunity ecology than the other four processes (but see Leibold *et al.* 2022a; Urban *et al.* 2008). However, given the accelerating pace of human-induced changes to ecosystems, it may become increasingly relevant (e.g., Heger *et al.* 2019). While we do not explicitly analyze novelty in the present framework, we include it as a placeholder among metacommunity processes to reflect its potential importance and to encourage future work on this emerging concept (**Figure 2**).

While the nature of these processes is relatively simple, interactions among them, especially when they occur in a heterogeneous landscape, can lead to extremely diverse outcomes. Work done to date in metacommunity ecology has characterized some possible outcomes into a set of 'archetypes' that can be seen as rough characterizations of a much broader spectrum (Leibold *et al.* 2004; Leibold & Loeuille 2015). These range from outcomes that strongly relate species distributions to abiotic environmental factors (called 'species sorting') to outcomes that include high stochasticity (these include 'patch dynamics' and 'neutral theory' archetypes) to intermediate outcomes (that include 'mass-effects', 'harlequin patch dynamics', and 'priority effects'). Although these classic metacommunity archetypes span only a limited area of the full process parameter space, they can serve as useful baseline reference points (Thompson *et al.* 2020).

As a first approximation, three of the five processes described above can be studied using Joint Species Distribution Models (JSDMs, **Box 1**). Although there are several technically distinct implementations of such models (e.g., Ovaskainen *et al.* 2017; Pichler & Hartig 2021), they provide a flexible framework to estimate species-specific environmental and spatial effects, infer pairwise species-species associations, and predict emergent community-level patterns. JSDMs can also be used to partition the total variation in community composition among sites in a metacommunity into components attributable to measured environmental factors, spatial structure reflecting dispersal patterns, co-distributions potentially driven by species interactions (Leibold *et al.* 2022b; Ovaskainen *et al.* 2017), and unexplained residual variation (that includes stochasticity and novelty). While such methods have important limitations (e.g., (Blanchet *et al.* 2020; Poggiato *et al.* 2021; Zurell *et al.* 2018), ongoing methodological advances can be expected to improve their capacity to represent complex ecological processes, even if stochasticity and novelty will likely remain challenging to capture explicitly.

One key feature of JSDMs, that contrasts with previous approaches like variation partitioning of community data, is that they can be used to isolate how each species in a metacommunity affects the overall structure of the metacommunity (Leibold *et al.* 2022b; Ovaskainen *et al.* 2017). Similarly, they can also be used to assess how each locality in a landscape affects overall metacommunity structure (Leibold *et al.* 2022b). Consequently, it is easier to diagnose which species and which sites are most important in determining the overall structure of a metacommunity (**Box 1**). By partitioning co-occurrence, environmental, and spatial components of species distribution patterns, JSDMs allow us to better understand the relative importance of these processes across landscapes. This can guide conservation and restoration efforts. The strength of these processes influences key metacommunity attributes, including biodiversity, productivity, or stability (e.g. Gravel *et al.* 2011; Shoemaker & Melbourne 2016). These insights may also inform sustainable harvesting and use of natural resources by revealing how metacommunity dynamics respond to management and policy interventions.

Meta-CHANS: Contextualizing metacommunity ecology with structured decision-making and socio-economic elements of CHANS

Our aim here is to link ecological dynamics, approached through metacommunity ecology, with human activities by integrating structured decision-making into a CHANS perspective. **Figure 3** provides an overview of our general approach. Integrating multiple spatial scales with the CHANS framework is essential to better understand the links and feedback routes between human and natural systems (Kramer *et al.* 2017). Metacommunity processes connect local (green, left) and landscape-scale (blue, right) components of the natural system, and management actions carried out at these scales therefore have both local and landscape-level ecosystem consequences by altering the relative strength of these processes. A general decision-making scheme used in conservation science (e.g., Backstrom *et al.* 2018; Gregory *et al.* 2012) is integrated (shown in brown at both scales) with a conceptual approach directed at policy-making (Daily *et al.* 2009), which represents the key socio-economic elements of the CHANS framework (gray).

The final elements of structured decision-making (optimization and implementation) are shared across scales to emphasize that management options should be evaluated and coordinated jointly rather than in isolation. In parallel with structured decision-making, local and landscape-level management choices lead to ecosystem consequences through changes in the relative strength of metacommunity processes. These consequences contribute to NCP and re-enter the structured decision-making cycle through the evaluation and optimization steps.

The gray CHANS elements depict how ecological outcomes influence societal values, which interact with institutions and policy to modify the decision context (e.g., through regulations or incentives). These feedbacks can alter utility assessments and thereby influence future management priorities. Local components are often more transparent and directly manageable, whereas landscape components typically act more slowly but more persistently. Explicit attention to cross-scale interactions – such as enhancing connectivity, increasing habitat heterogeneity, or coordinating restoration across sites – creates opportunities to directly regulate metacommunity processes and improve both regional biodiversity and local ecosystem outcomes.

Together, the framework illustrates how local and landscape-level management actions influence metacommunity processes, how these changes cascade into ecosystem consequences and NCP, and how feedbacks between natural and social systems shape future decisions and sustainability.

Application of the Meta-CHANS framework

The proposed framework incorporates basic ecological principles into the analysis and implementation of CHANS. We next illustrate how this framework could be used in conservation policies and management by providing testable hypotheses (**Table 1** and **Figure 4**). **Table 1** outlines the testable hypotheses emerging from the Meta-CHANS framework, linking each general hypothesis to specific mechanisms, empirical tests, and expected outcomes. **Figure 4** presents a conceptual overview of the four main hypotheses, summarizing how local and landscape-scale management actions interactively influence metacommunity processes and resulting biodiversity and ecosystem outcomes. **Figures S1-S3** and **Texts S1-S3** in the **Supporting Information** provide further illustration especially for H1, where we show predicted shifts in the relative strength of metacommunity processes after different local and landscape-level management interventions in three landscapes, covering riverine management, urban green space planning, and invasive species management. Our goal here is to illustrate how different management alternatives might be likely to produce alternate likely outcomes that can inform decision optimization. Some of these management alternatives are more inspired by human utility, while others primarily aim for restoration. It should also be noted that the results of the management choices presented here as part of the Meta-CHANS framework will also vary a lot among taxa with different life cycles, trophic position, body size, or dispersal abilities, and therefore, these cases should be only used as hypothetical, complementary examples to illustrate the manifold consequences of management choices for metacommunities and ecosystem attributes.

While the hypotheses summarized in **Table 1** can be tested empirically, carrying out these explicit tests remains a challenge due to current data availability. As discussed in **Box 2**, even large-scale monitoring programs rarely collect spatially explicit ecological and environmental data in a coordinated way that allows before-after or cross-system comparisons. Most datasets are established after major interventions or lack pre-impact baselines. To bridge this gap, future data collection should be designed accordingly, to enable testing predictions (**Table 1**) and contribute with the empirical application of the Meta-CHANS framework in real-world conservation contexts.

Case study: optimizing grassland management intensity to favor diverse native biota

To illustrate the principle of how the Meta-CHANS framework can inform real-world conservation decisions, we use the example of a grassland management experiment to control the plant *Jacobaea aquatica*, a native species that has become locally overabundant in Central European wet meadows (Krieger *et al.* 2022a, b). These semi-natural grasslands are of high conservation value and simultaneously serve as sources of hay, highlighting the close coupling between biodiversity management and human land use (**Fig. 3**, “Utility assessment” and “Define the decision context”). *Jacobaea aquatica* is toxic to livestock and humans, creating a direct human-utility dimension and a strong incentive for management intervention (Gottschalk *et al.* 2018). This grassland system provides an opportunity for examining how local and landscape-scale management could interact to influence biodiversity outcomes through metacommunity processes. As no reference data was available from before applying the different management treatments, we compare different levels of mowing intensity after a couple of years in the same landscape of wet meadow fields (details on the study site and treatments are provided in **Text S4** in the **Supporting Information**). A similar approach could be readily adopted for other empirical data that meet the key data pre-requisites outlined in **Box 2**.

At the local scale, grassland mowing intensity (**Fig. 3**, “Local management”: manage habitat quality and overabundant species) could change the strength of both abiotic and biotic selection (**Fig. 3**, “Metacommunity processes”). Frequent mowing (control treatment) maintains open, light-rich conditions that favor *J. aquatica*, a disturbance-adapted species capable of colonizing bare soil patches. In contrast, reduced mowing (low-intensity management) increases shading and litter accumulation, strengthening local competition and suppressing the invader, as seen by the data analysis in **Figure 5** (see also **Fig. 3**, "Local ecosystem consequences"). These dynamics exemplify stronger density-dependent selection and a higher importance of biotic interactions operating within local communities under lower mowing intensity. Unexplained variation in species composition also declined with reduced mowing intensity, suggesting that community assembly became more deterministic and less influenced by stochastic processes as management disturbance decreased (**Fig. 3**, "Estimate consequences of alternatives").

At the landscape scale, the spatial configuration of grasslands and the synchronization of management regimes could, in principle, determine dispersal pathways and recolonization probabilities (**Fig. 3**, "Define the decision context" to "Landscape management": manage connectivity across sites). In this experimental system, spatial variation was limited, but in other cases, one might think about landscape-level synchronization of management (**Fig. 3**, "Landscape management": coordinate regional management, "Identify objectives and develop measures" at the landscape scale). High connectivity among frequently mown sites could facilitate the dispersal of *J. aquatica*, while heterogeneous mowing patterns could reduce synchrony and constrain the spread of disturbance-adapted species (**Fig. 3**, "Develop management alternatives" at the landscape scale). Thus, landscape-level interventions could be more efficient if they are considered within the broader landscape mosaic that governs dispersal and environmental heterogeneity (**Fig. 3**, "Evaluate and optimize trade-offs").

Finally, the human system, including landowners' preferences, perceptions, and incentives, ultimately determines which management strategies are adopted and maintained, creating feedback to ecological outcomes (human drivers/constraints in **Fig. 3**). In this system, management decisions are shaped not only by ecological goals but also by economic and social considerations, such as livestock safety and agricultural productivity (**Fig. 3**, "Utility assessment"). While our case study does not yet capture these feedbacks explicitly, it represents an important first step toward the empirical application of the Meta-CHANS framework. It demonstrates how existing ecological data can be used to infer links between management intensity and metacommunity processes, providing a foundation for future studies that explicitly integrate socio-economic drivers and adaptive feedback. Analyses like this also offer an objective tool for evaluating how management interventions jointly affect biodiversity conservation and human utility across landscapes.

Discussion and Conclusions

Metacommunity ecology offers an important structural foundation for integrating ecological processes with human activities, providing tools for understanding how biodiversity responds to anthropogenic stressors (McFadden *et al.* 2023; Simmons *et al.* 2021), or even conservation management (Chase *et al.* 2020; Patrick *et al.* 2021). Our goal is to provide a framework using

Coupled Human And Natural Systems (CHANS; Liu *et al.* 2007, 2021) outlining how recent advances in metacommunity theory and methods can inform environmental decision-making linked to human activities across spatial scales. We also demonstrate the empirical applicability of Meta-CHANS through a grassland management case study that experimentally tested how local mowing intensity shapes metacommunity processes and overabundant species dynamics. Our empirical demonstration complements our conceptual examples (described and discussed in the Supplemental Information) and illustrates how the framework can bridge ecological theory and management practice in diverse applications of conservation and restoration ecology. We propose that this is facilitated by several ongoing developments in the field.

First, the rapid methodological progress in metacommunity ecology allows the analysis of complex, species-rich communities. While earlier work in metacommunities was useful for smaller species sets, the rise of eDNA-based metabarcoding methods and the use of artificial intelligence (Fajgenblat *et al.* 2025; Ruppert *et al.* 2019; Waldock *et al.* 2024) can now help detect formerly unseen members of these communities, offering deeper resolutions of community patterns (Hartig *et al.* 2024). There remain significant challenges regarding the inference of processes from these patterns (Blanchet *et al.* 2020), which is also critical for understanding the consequences of human activities. However, there is an upsurge to increase the capability to analyze spatial community data with powerful, pattern-finding statistical tools such as JSDMs and related methods (Leibold *et al.* 2022b; Ovaskainen *et al.* 2017, 2025; Pichler & Hartig 2021) as well as the more conventional analysis using multivariate analyses coupled with variation partitioning approaches. Future work in simulation methods and alternative approaches is also likely to continue to improve pattern-to-process inference (Chang *et al.*

2021; Guzman *et al.* 2022; Huang *et al.* 2024; Leibold *et al.* 2025; Thompson *et al.* 2020) and thus increase the value of metacommunity ecology to management and policy.

Second, taking a metacommunity perspective can improve practical decision-making within the structured decision-making framework described by Gregory *et al.* (2012). This widely-used framework combines the various decision-making tools used in the management of complex ecosystems as part of CHANS, making it a powerful decision tool (Martin *et al.* 2009). Metacommunity approaches can be utilized to describe initial conditions in nature and then forecast the impact of management actions at local and regional scales (**Figure 2c**). While the reliability of these projections depends on how well the pattern-to-process inference works, the currently available tools already provide useful insights and ongoing work will likely continue to improve. By exploring several management options and their impacts on landscape-level dynamics, this framework can support more informed decision-making that builds on the metacommunity perspective enabling to set local and regional management options into context.

Third, we place our proposed framework within a broader socio-economic and policy context that focuses on the enhancement of ecosystem services and NCP. We address this with a simplified version of the general approach of Daily *et al.* (2009), and suggest that more complex frameworks would likely lead to similar conclusions (e.g., Díaz *et al.* 2018; Mace 2014; Mandle *et al.* 2021; Soga & Gaston 2020; Xu & Peng 2022). Within the Meta-CHANS framework, the most important element of this dynamic is the use of regulations or incentives that alter the utility functions that affect the optimization of management decisions, in interaction with other economic and ecological aspects. While the actual utility functions can be altered by a range of complex cultural or technocratic factors, mostly beyond the scope and scale of metacommunity ecology, ecological factors can still contribute to altering societal values, for example by changing public perceptions of the complexity and aesthetic values of nature. While the NCP - ecosystem services occupy a key position in the framework we build on (Daily *et al.* 2009), here we chose to keep it simple and general in order to allow us to focus more on the connection to metacommunities. However, this could be further expanded within the Meta-CHANS framework in the future.

Applying the Meta-CHANS framework has several practical implications, such as the use of sophisticated monitoring and analytical methods. For example, while JSDMs can be powerful tools in the analysis of metacommunity data, their complexity can mean a methodological barrier or lead to misinterpretations. The development of standardized, user-friendly approaches and platforms would be a critical step forward to their wider application. This suggests that classic empirical metacommunity tools will likely remain in use for a while, given their relatively simple and easy-to-use toolkits. Their application for study cases, e.g. for comparing ecosystem states in a before-after-control-impact setup making these cases highly comparable, could still yield useful and reliable data for management.

One of the challenges in applying our proposed framework is the potential mismatch between the scales of metacommunity processes and those involving decision making processes. Here, we simplified reality by assuming two levels of spatial scale in both realms, and assuming that they match. Our conceptual examples (**Fig. S1-3, Text S1-S3**) illustrate that this can offer important perspectives. Yet, in many cases, what is called regional processes in metacommunities do not necessarily correspond to the scales at which larger policy decisions are made, so that it is conceivable that both local and regional processes of a given regional metacommunity relate to local structured decision making, whereas policies influence country and continental scale processes instead. In our river example (see **Fig. S1** and **Text S1**), for instance, policies may affect how rivers are managed and protected across a very large political entity (e.g. Europe), whereas both the management of a given river catchment as well as the management of different habitats within such a catchment are part of (different) decision making processes that are considered local in our example. This matching of spatial scales and the more precise outcomes of spatial mismatches between policy making and metacommunity processes deserve further study.

It is also important to recognize that nature does not always conform to theoretical expectations. Ecological systems are notoriously (and grandiosely) idiosyncratic, and unexpected outcomes frequently emerge from complex feedbacks and context-dependent interactions. These dynamics are often shaped by the natural history of the organisms involved, which are difficult to generalize and rarely captured in abstract frameworks. As a result, predictions based on metacommunity theory will always involve some levels of uncertainty and should be rather seen as robust approximations, identifying likely outcomes that capture key patterns. Our proposed framework should thus be seen as a flexible guide that can support adaptive management refined over time through ongoing monitoring.

Our proposed framework also highlights the need for interdisciplinary collaboration to improve the integration of the ecological and human systems in Meta-CHANS. This coupling could be improved with input from ecologists with advanced methodological skills, practitioners with local knowledge and authority for decision-making, and policymakers with the capacity of making changes to legislation. Most of the examples we provide here are feasible at lower levels of governance, e.g. regional municipalities, cities, or national parks, where habitat networks can be managed using the metacommunity concept. Here, ecologists and conservation practitioners could directly collaborate, combining robust data, practical experience, and knowledge on socio-economic limitations, leading to informed decision-making. These mutual insights could be further improved by combining our framework with a social-ecological network approach (e.g., Bodin & Tengö 2012; Kluger *et al.* 2020; Rickowski *et al.* 2025). The insights can help bridge the gap between basic ecology and practical conservation by inspiring ecological research towards real-world, solution-oriented approaches. Future studies could expand this empirical dimension by applying the Meta-CHANS framework to long-term monitoring datasets, citizen science programs, or experimental manipulations across spatial scales.

Strengthening our understanding of how nature and human dynamics are coupled remains a major challenge. Here, we have focused on the multiscale dynamics shared by ecological and social systems. These dynamics operate at both local and regional scales. Most of the processes occur at local scales where it is relatively straightforward to understand the dynamic feedback that is only indirectly affected by what happens elsewhere. And both have dynamics that occur at larger spatial scales. Some of these larger-scale effects simply reflect aggregated effects of local dynamics, but others reflect feedback routes that transfer the consequences of local dynamics across space through both metacommunities and human activities in non-additive ways. We argue that a metacommunity approach on the nature side can be effectively paired with structured decision-making and NCP frameworks on the human side. This can enhance our understanding of the dynamics of CHANS and improve the relevance of ecology in addressing human-driven ecosystem changes through the resulting Meta-CHANS framework.

Acknowledgements

We would like to thank all participants of the workshop for the discussions that inspired this work. We also thank Veronica Frans, Csaba F. Vad, and members of the Leibold and Horváth labs for helpful discussions during the writing process, and the suggestions of two anonymous reviewers that greatly improved the manuscript. We thank Marie-Therese Krieger for her helpful correspondence and for providing additional spatial coordinates for the case study. The core idea of this work resulted from a Hi Knowledge (https://www.hi-knowledge.org) workshop funded by IGB. The work of ML and ZH was further supported by U.S. NSF-AWD08828. ZH was additionally supported by the National Multidisciplinary Laboratory for Climate Change (RRF-2.3.1-21-2022-00014) project within the framework of Hungary's National Recovery and

Resilience Plan supported by the Recovery and Resilience Facility of the European Union, OTKA FK146095 (NKFIH), the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA), and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (grant number BO/00418/24/8). SCJ considers this work a contribution to the Collaborative Research Centre 1439 RESIST funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation, CRC 1439/2, project number: 426547801). FH acknowledges support by the Chinese Academy of Sciences (E355S122). LG is supported by the Deutsche Forschungsgemeinschaft (DFG, Project number 511084840). LDM is supported by the KU Leuven Research Council project C16/2023/003 and by an IGB start-up funding.

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Figure and Table Legends

Figure 1 Two approaches for decision-making in CHANS and their integration. **(a)** Sequential steps of structured decision-making, applicable to relatively small-scale issues that can be implemented in relatively short time (Gregory *et al.* 2012). **(b)** Key elements in CHANS across multiple socio-political dimensions, with the aim of integrating ecosystem services (based on Daily *et al.* 2009). Here, elements from the human system are shown in gray, where ecosystems (green) and their services are integrated into the decision-making process. This loop typically operates at longer timeframes than the structured decision-making loop. (**c)** Direct integration of structured decision-making into the human system side of CHANS, including nature's contributions to people (NCP) and ecosystem services (ES) at local and global scales.

Figure 2 (a) Local- and landscape-scale processes jointly shape biodiversity and ecosystem dynamics. Local-scale management targets conditions within individual sites, while landscape-scale management can address spatial connectivity and cross-site interactions. **(b)** Metacommunities are shaped by the relative strength of five main processes: environmental factors (optimizing selection), spatial processes (dispersal), biotic interactions (co-distribution), stochasticity and novelty processes. The former three can be expressed by partitioning variation within communities (ternary plot presentation refers to JSDM outputs, see **Box 1**), while unexplained variation can reflect both stochasticity and novelty. Management actions can affect the composition of local communities by influencing the relative strength of these processes, having profound effects across scales. **(c)** Decisions are based on options (mostly implicitly) with which multiple possible new conditions of the natural system might be achieved. (The relative strength of processes, indicated by the position of scores in the ternary plots, are hypothetical and are only used to illustrate the multitude of changes these decisions might induce.)

Figure 3 A conceptual framework integrating metacommunity ecology with structured decision-making within Coupled Human and Natural Systems (CHANS). The framework links ecological dynamics (natural system) with socio-economic feedback (human system) across local and landscape scales. Local-scale (green background, left) and landscape-scale elements (blue background, right) represent management actions, effects on metacommunity processes, and resulting ecosystem consequences. The brown elements show structured decision-making steps (after Gregory *et al.* 2012), illustrating how management objectives, alternatives, and evaluations are developed and implemented. The gray elements (adapted from Daily *et al.* 2009) depict the broader CHANS context, including policy, institutions, and societal values that influence and are influenced by ecological outcomes through feedback on utility and decision-making.

Figure 4 A conceptual overview of the testable hypotheses linked to the Meta-CHANS framework, presented in **Table 1**. (The use of barplots representing metacommunity processes follows **Figure 2**.)

Figure 5 Application of the Meta-CHANS framework to a grassland management experiment aimed at controlling the plant *Jacobaea aquatica* in Central European wet meadows. **(a)** Mean ±

SE site-level variance (R^2) in species composition explained by the effects of the environment, space, and co-distribution among species, as well as the unexplained fraction, under three mowing intensities. **(b)** Ternary plot showing the relative contributions of the effects of the environment, space, and co-distribution to the explained share of site-level variation in species composition. Mean site scores under different mowing intensity levels are indicated by larger points. **(c)** Mean cover of *J. aquatica* (± SE), showing its decline under reduced mowing.

Table 1 Testable hypotheses emerging from the Meta-CHANS framework. See also Supplementary **Figures S1–S3** for illustrative examples on local and landscape-scale management alternatives in three different types of landscapes, with the predicted relative strength of metacommunity processes before and after different management interventions.

Figures

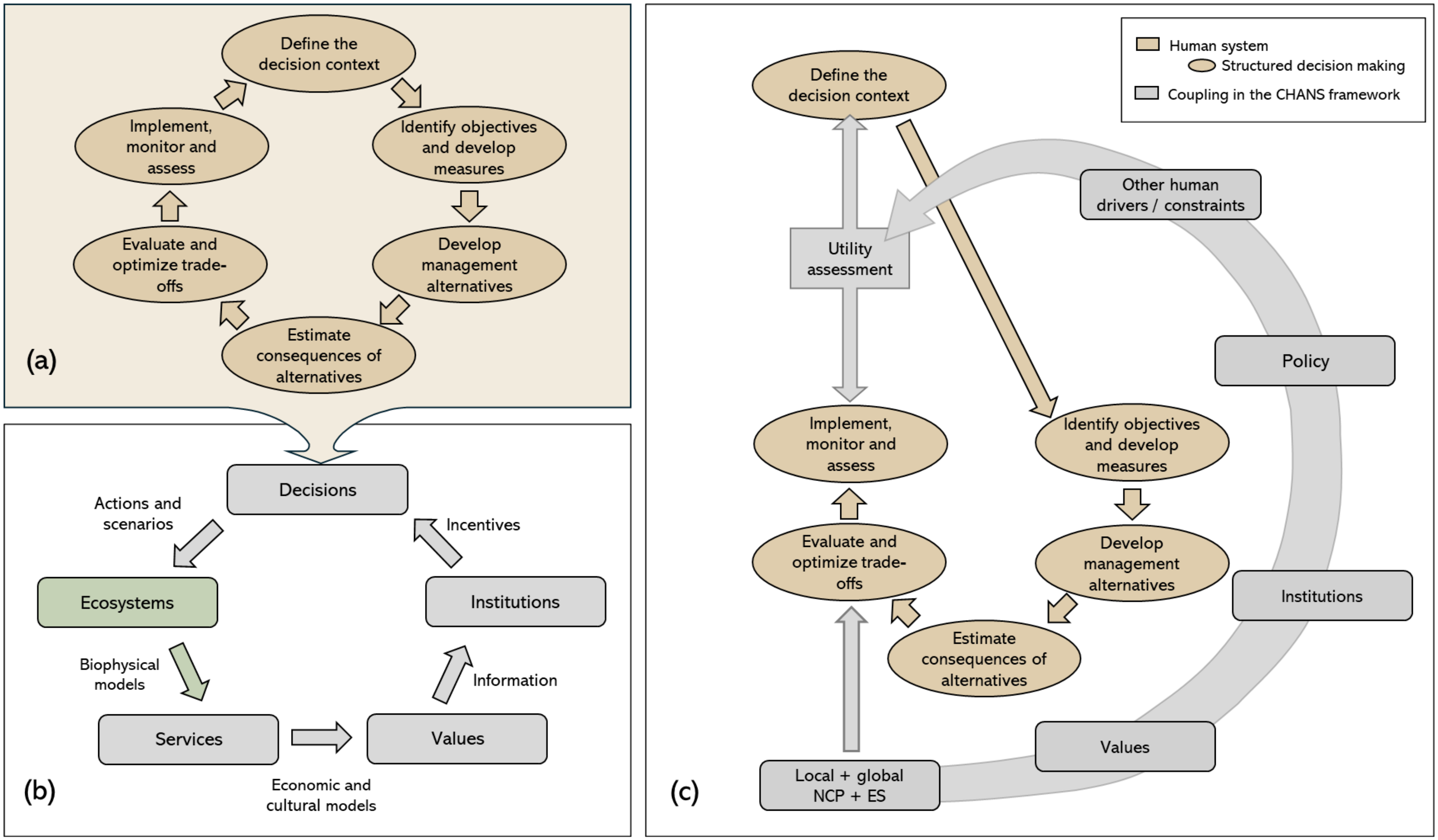
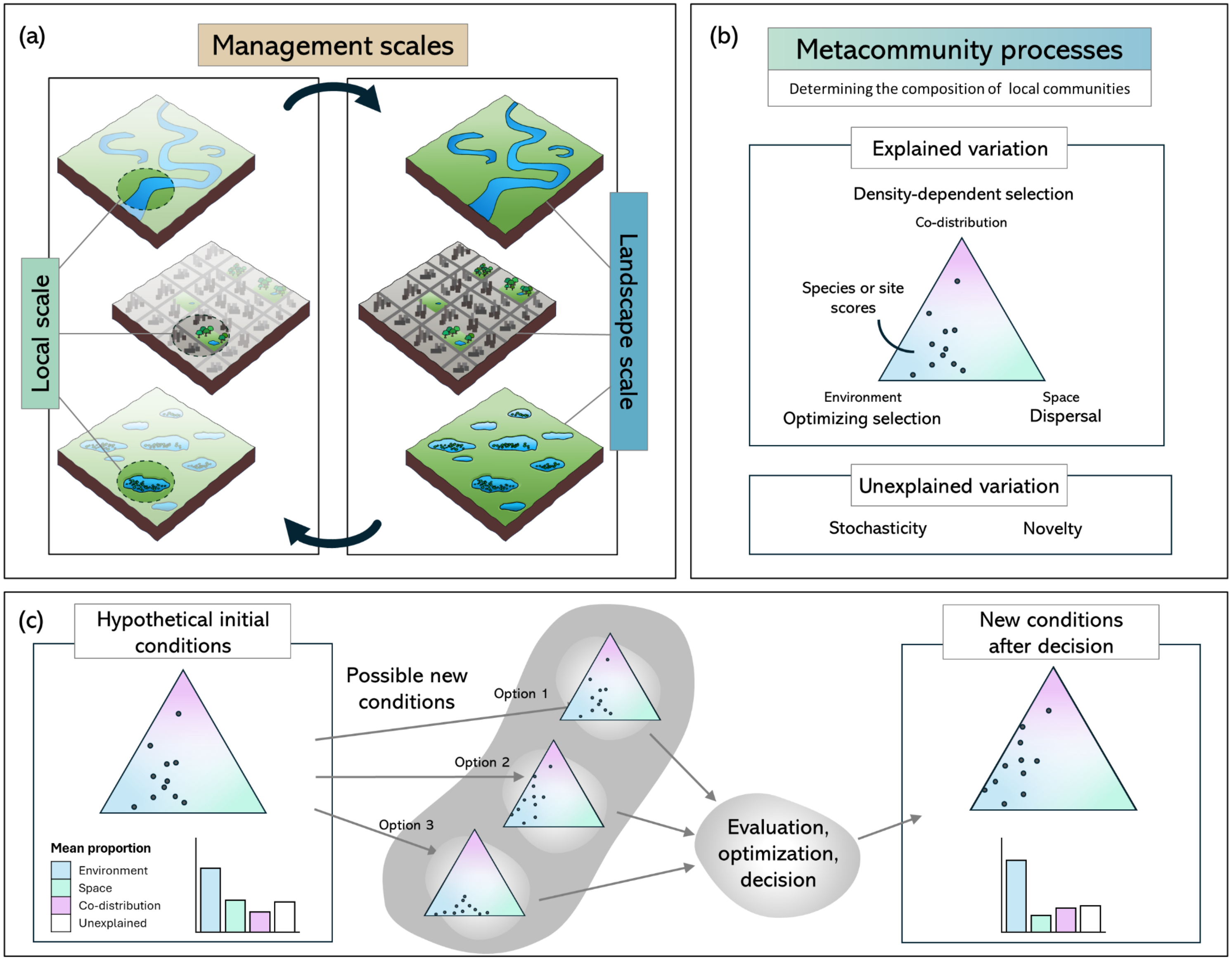
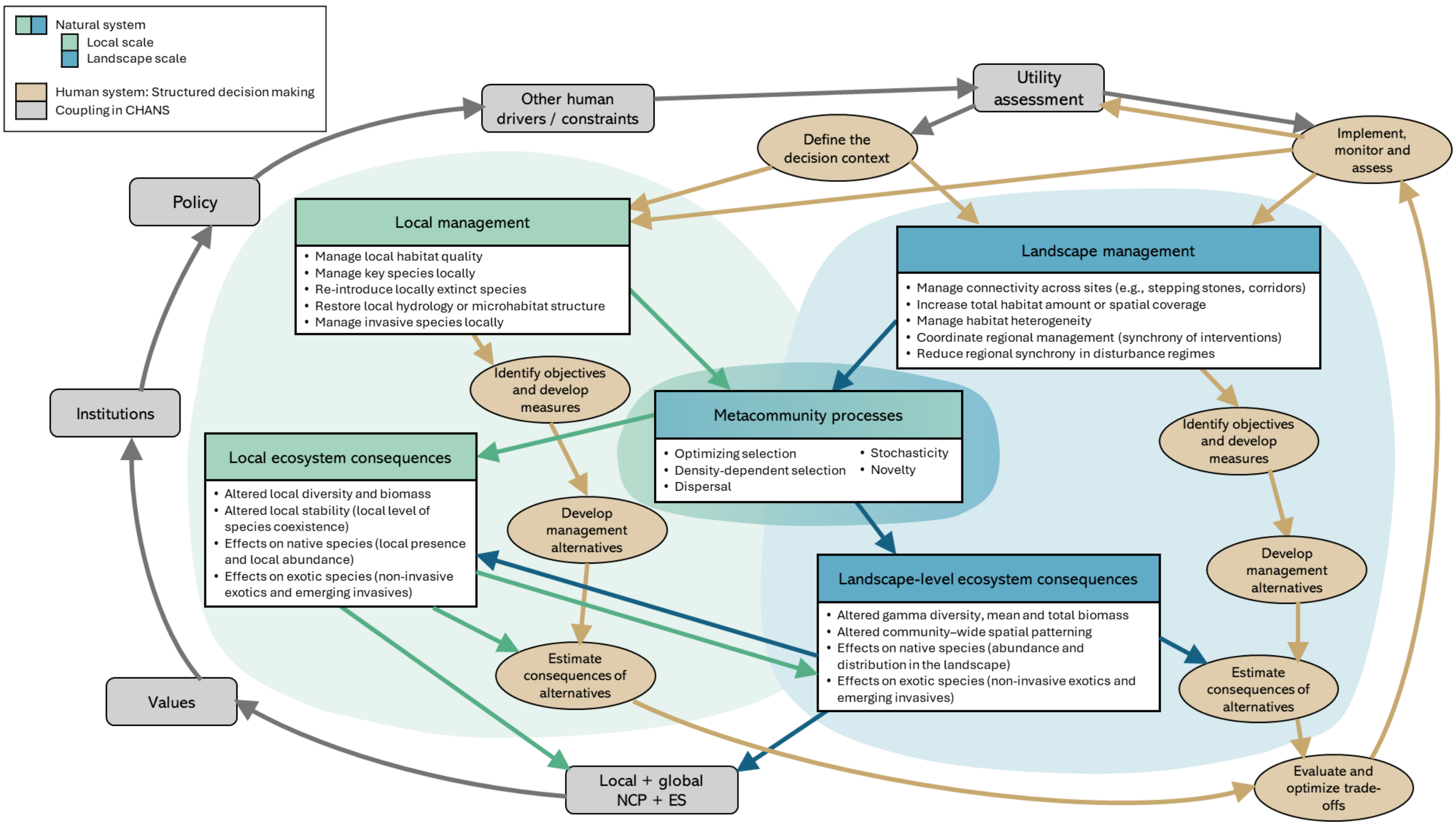


Figure 1



(a)
Management scales
Local scale
Landscape scale
(b)
Metacommunity processes
Determining the composition of local communities
Explained variation
Density-dependent selection
Co-distribution
Species or site scores
Environment
Optimizing selection
Space
Dispersal
Unexplained variation
Stochasticity
Novelty
(c)
Hypothetical initial conditions
Mean proportion
Environment
Space
Co-distribution
Unexplained
Possible new conditions
Option 1
Option 2
Option 3
Evaluation, optimization, decision
New conditions after decision

Figure 2



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778 **Figure 3**

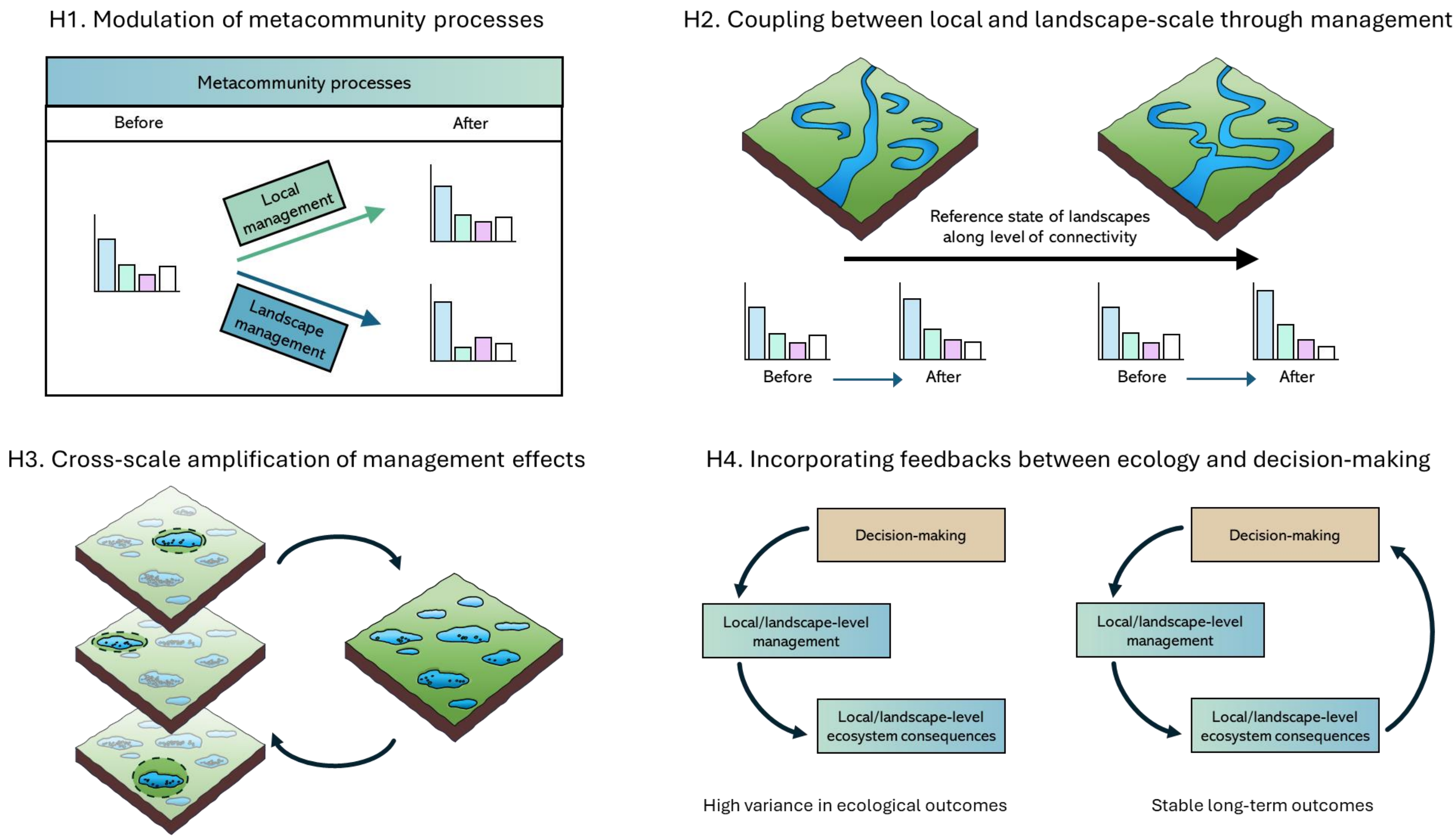
H1. Modulation of metacommunity processes
Metacommunity processes
Before
After
Local management
Landscape management
H2. Coupling between local and landscape-scale through management
Reference state of landscapes along level of connectivity
Before
After
Before
After
H3. Cross-scale amplification of management effects
H4. Incorporating feedbacks between ecology and decision-making
Decision-making
Local/landscape-level management
Local/landscape-level ecosystem consequences
Decision-making
Local/landscape-level management
Local/landscape-level ecosystem consequences
High variance in ecological outcomes
Stable long-term outcomes

Figure 4

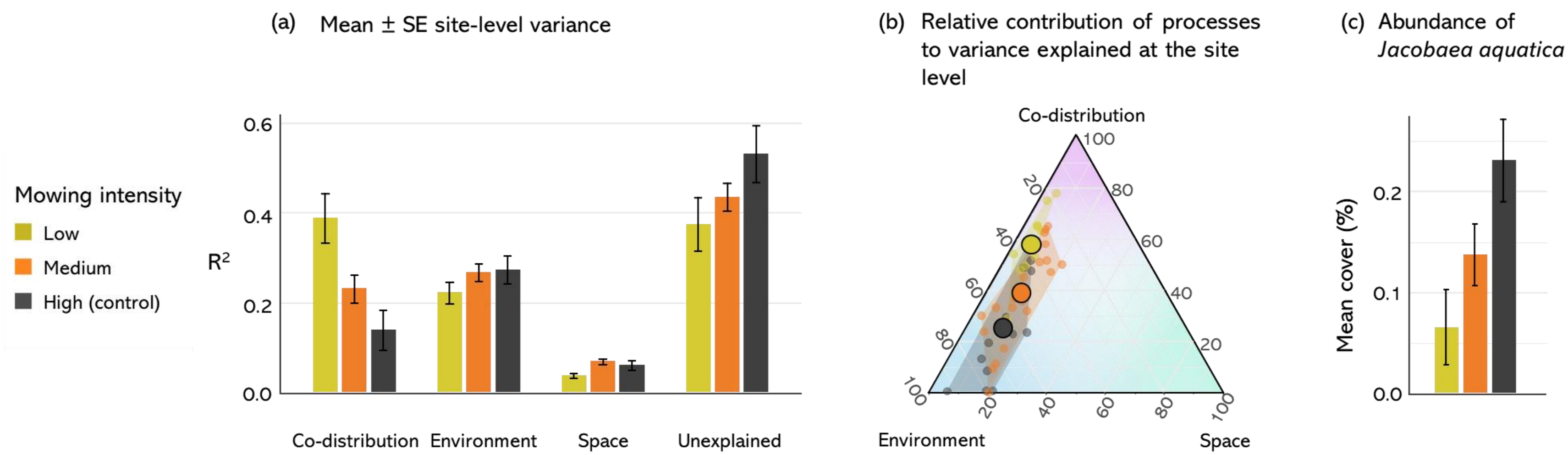
(a) Mean ± SE site-level variance
Mowing intensity
Low
Medium
High (control)
R²
0.6
0.4
0.2
0.0
Co-distribution
Environment
Space
Unexplained
(b) Relative contribution of processes to variance explained at the site level
Co-distribution
100
80
60
40
20
Environment
Space
(c) Abundance of Jacobaea aquatica
Mean cover (%)
0.2
0.1
0.0

Figure 5

Tables

General hypothesis	Specific hypothesis	Empirical test	Prediction
H1. Modulation of metacommunity processes	Local conservation management (e.g., habitat restoration, managing invasive species, local hydrological or vegetation management) alters biodiversity by shifting the relative strengths of metacommunity processes.	Compare the relative strengths of metacommunity processes before and after local management interventions using JSDMs or other process-inference tools.	Local interventions that improve environmental quality or reduce biotic pressure (e.g., removal of invasive species) strengthen abiotic selection, lessen biotic interactions, and reduce stochasticity, often increasing local diversity and stability.
	Landscape-level management (e.g., connectivity restoration, coordinated habitat creation, or multi-site rewilding) modifies metacommunity dynamics by altering dispersal and spatial structuring.	Compare the relative strengths of metacommunity processes before and after landscape-level management interventions using JSDMs or other process-inference tools.	Landscape-level actions that enhance connectivity and regional habitat heterogeneity generally increase dispersal and abiotic selection, leading to higher beta and gamma diversity and more stable regional metacommunities. However, excessive connectivity leads to homogenization (mass effects).
H2. Coupling between local and landscape-scale through management	Local management outcomes depend on the regional ecological and policy context.	Compare metacommunity patterns, processes, and NCP before and after local restoration under different regional connectivity levels (e.g., in riverine regions with different levels of fragmentation due to dams).	Local restoration leads to stronger biodiversity gains in a more connected regional network.
	Regional management outcomes depend on cumulative local interventions.	Compare changes in metacommunity patterns, processes, and NCP across regions differing in the number or coordination of local interventions (e.g., removal of invasive species).	Regions with coordinated local actions will show stronger biodiversity gains and ecosystem stability than those with isolated efforts.
H3. Cross-scale amplification of management effects	Landscape-level actions produce larger and longer-lasting ecological effects than isolated local measures.	Compare biodiversity and NCP outcomes and the response of metacommunity processes following regional versus local-scale interventions (e.g., coordinated invasive species management vs. single-site removal).	Regional actions will yield stronger, more persistent improvements in biodiversity and ecosystem services, though their effectiveness will depend on local habitat quality and temporal consistency in management.
H4. Incorporating feedbacks between ecology and decision-making	Decisions are more sustainable when management explicitly considers feedback between ecological outcomes and human benefits.	Compare long-term variance in NCP outcomes (e.g., water quality) between systems with and without the integration of ecological feedback. An example can be a landscape where adaptive lake management regularly monitors biodiversity and adjusts water-use policies accordingly vs. where management actions are based on short-term human demand only.	Systems that explicitly incorporate feedback between ecological outcomes and human decision-making show greater long-term stability and adaptability, enhancing both ecological sustainability and social acceptance of management.

Boxes

Box 1 - Joint Species Distribution Models (JSDMs) and their relevance for biodiversity conservation

JSDMs are elaborations of long-utilized Species Distribution Models (SDMs). While SDMs assess how environmental factors and spatial effects related to dispersal-driven spatial patterns of individual species, they do not account for species interactions and largely overlook stochasticity, which JSDMs can address. JSDMs are implemented in various statistical packages that differ in their technical approach, undergoing rapid development to improve their utility (see e.g. Ovaskainen *et al.* 2025; Pichler & Hartig 2021; Rahman *et al.* 2024). Here we focus on their conceptual contribution to understanding metacommunity dynamics.

JSDMs provide two basic types of outputs (Ovaskainen *et al.* 2017; Pichler & Hartig 2021). The first can partition variation in the composition of sites attributable to different types of predictors: effects of environment (reflecting mostly abiotic factors), space (effects of dispersal), residual co-distribution among species (including especially species interactions), and randomness (reflecting largely the effects of stochasticity). The same can also be carried out for the contributions of each individual species. These effects can be visualized using ternary plots (Leibold *et al.* 2022b). The position of sites or species (as in **Figure B1**) in these ternary plots can inform us of the dominant processes driving community assembly for each site or species in a metacommunity as well as for the metacommunity as a whole (as the average of all the individual species). This can already inform conservation management about the factors that can best help conserve or control focal species (in the case of invasive or rare species). Similarly, site-based plots can help identify influential sites that are important in the distribution of species due to local environmental conditions or spatial position, serve as important 'arenas' for species interactions, or contribute with high stochasticity to species distributions. This can provide information for the prioritization of sites for biodiversity conservation.

JSDMs also estimate model parameters that can help identify which environmental gradients or spatial scales are the most important for species distribution, or which species groups share environmental responses. These parameters can further guide management with a deeper understanding of metacommunity dynamics.

It is important to understand that there are limitations to interpreting JSDMs, and e.g. unmeasured components of environmental features and spatial effects can bias and inflate the importance of co-distributions and stochasticity. There are also some important concerns regarding the robustness of pattern-to-process inference (Blanchet *et al.* 2020; Poggiato *et al.* 2021; Zurell *et al.* 2018), although this might be possible to some degree (e.g. Clark *et al.* 2018). Nevertheless, JSDMs are already a powerful tool that can deliver several types of information relevant for conservation management and its decision-making. The rapid development of this field will likely be further boosted by machine learning and AI methods in the near future.

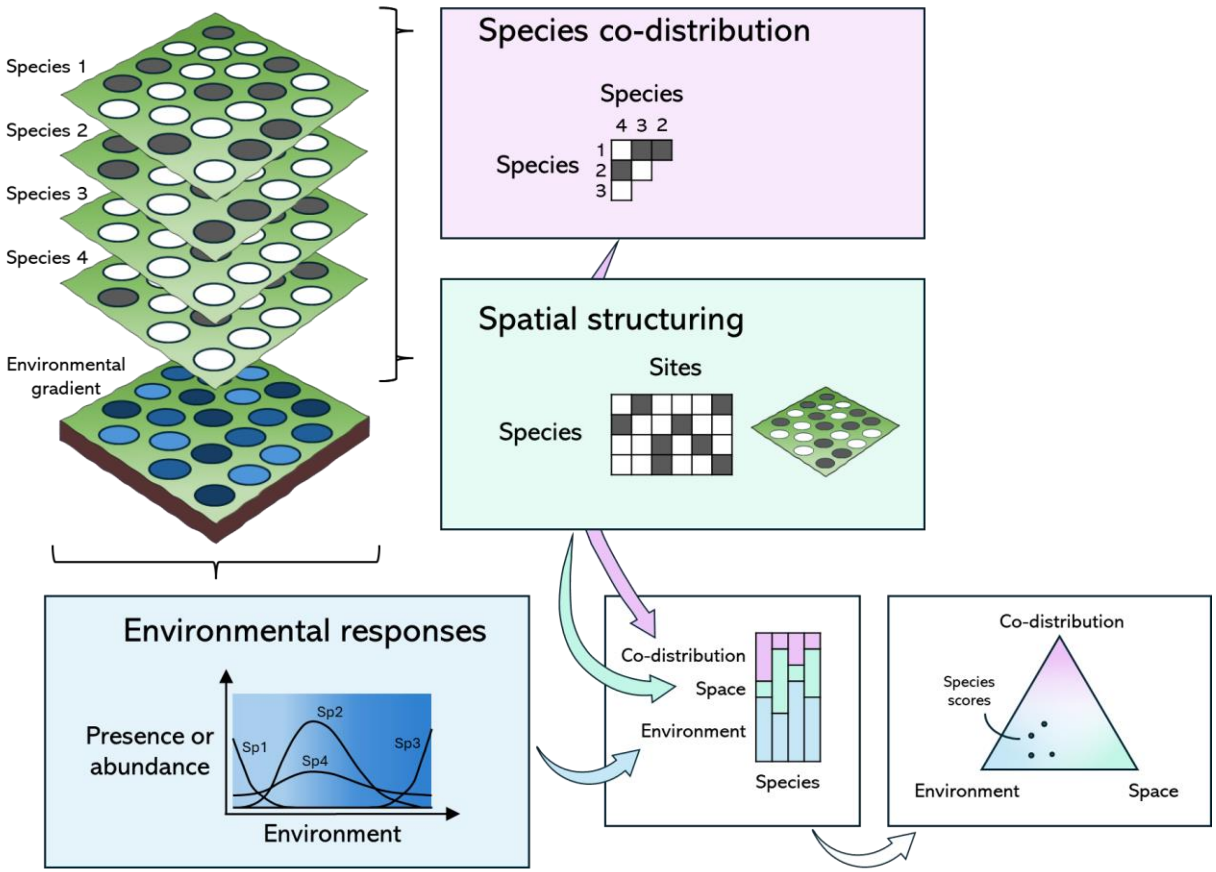

Figure B1: Decomposing landscape-level distribution patterns of members of a metacommunity into species co-distribution, environmental responses and spatial structuring with the help of JSDMs. The distribution of each species is described individually as a function of the landscape that describes the spatial location of each site and its measured environmental features (note that subsequent interpretation of these features should consider other possible but unmeasured environmental features). From this data, it is possible to hypothesize the environmental responses of each species (often as a Gaussian curve), its sensitivity to spatial structure (e.g. spatial scale, or geographic context), and an estimate of how it covaries with other species (here shown as a correlation matrix), indicative of both direct and indirect effects of species interactions. For each species, the residual variance is also an estimate that measures how much its distribution seems to be stochastic or cannot be explained with the available data.

Box 2 - Data needs for testing predictions and applying the Meta-CHANS framework

Despite rapid methodological progress, empirical validation of the framework through case studies remains constrained by fundamental data limitations. Surprisingly, although numerous monitoring programs exist across terrestrial and aquatic ecosystems, very few generate data suitable for analyzing coupled human-nature dynamics, as they require detailed metacommunity data both before and after management interventions. Most ecological datasets are collected after major interventions or environmental changes have already occurred, without comparable pre-impact baselines or sufficient replication across sites. Local environmental variables are often missing or measured inconsistently, and social or management variables are rarely integrated at the same spatial and temporal resolution. Geographic coordinates are also frequently incomplete or absent. As a result, even large-scale monitoring initiatives seldom allow before-after or cross-system analyses linking changes in the metacommunities to socio-economic drivers. This data limitation is analogous to long-term fragmentation research (see Horváth *et al.* 2019), where the similar lack of baseline datasets or the absence of environmental conditions constrain our ability to generalize beyond single case studies. Addressing this gap will require explicitly Meta-CHANS-oriented monitoring designs that collect community, environmental, spatial, and human-system data with comparable spatial and temporal resolution.

Supporting Information

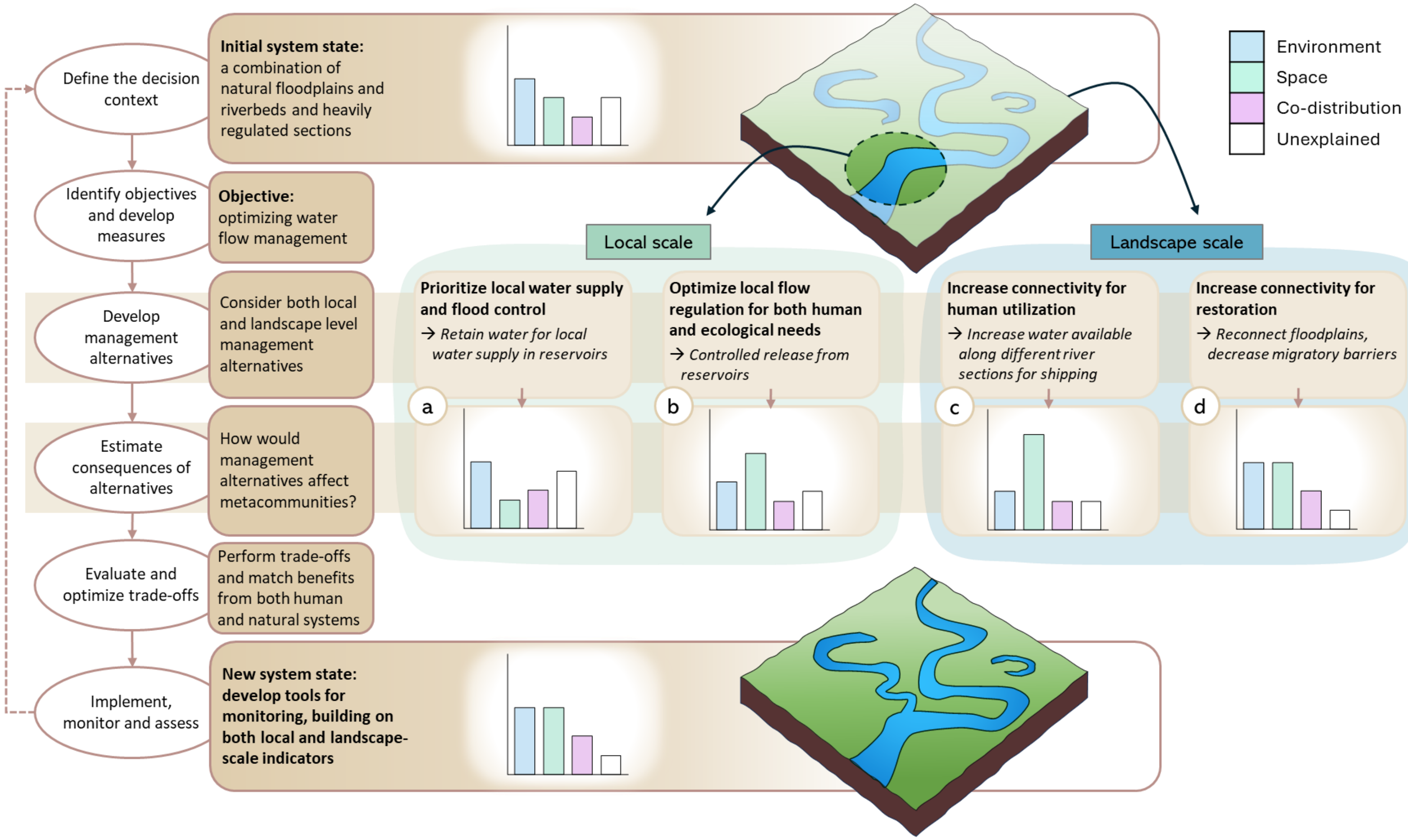

Figure S1 An example of a riverine system heavily impacted by human activities. We imagine that the general objective here is optimizing water flow management, but local (cases “a” and “b”) and landscape-level alternatives (“c” and “d”) might lead to different relative strengths of metacommunity processes (color coding follows **Figure 2** in the main text).

Text S1 River management

Modern riverscapes typically consist of heavily regulated, fragmented sections alongside a few intact floodplain and riverbed remnants, embedded in complex decision contexts (Langhans *et al.* 2019). Due to their naturally high connectivity, dispersal is a key metacommunity process influencing species distributions and ecosystem properties in river ecosystems. Human activities such as dam constructions can strongly influence local habitat conditions, leading to strong abiotic selection and altering competitive interactions among species (He *et al.* 2024).

Local scale management (cases "a" and "b" in **Figure S1**) focuses on stabilizing water supply while incorporating local flood risk reduction. Retaining water in reservoirs ("a") reduces connectivity and changes the strength of abiotic selection (it often becomes stronger upstream, and weaker downstream). It increases stochastic effects in fragmented river sections. In contrast, dynamic flow regulation ("b") balances water use with biodiversity needs, enhancing downstream dispersal of some taxa (e.g. plants and plankton) with controlled water release from local reservoirs. However, when flow regulation is abrupt or poorly timed, fluctuating conditions weaken abiotic selection and homogenize communities. There has been increasing interest in using controlled water release to mimic natural flow regimes (i.e. environmental flow) to fulfill ecological needs of species in downstream sections (Arthington *et al.* 2024). The functional elements of natural flow regimes brought back by environmental-flow implementation could facilitate the recovery of extirpated native species due to altered flow regimes downstream of dams, which could enhance overall diversity when implemented effectively.

Cases "c" and "d" are both landscape-level management alternatives, with a similar aim (increasing connectivity), but with different approaches. Case "d" prioritizes ecological restoration by reconnecting floodplains, removing migratory barriers and ensuring minimum ecological flows to support multiple taxa. Case "c" also increases connectivity but primarily for human use. This might result in similar outcomes as "d", as ships and migratory animals share some of the same physical barriers (e.g. dams). Despite differing objectives, both approaches may alter metacommunity processes in similar ways.

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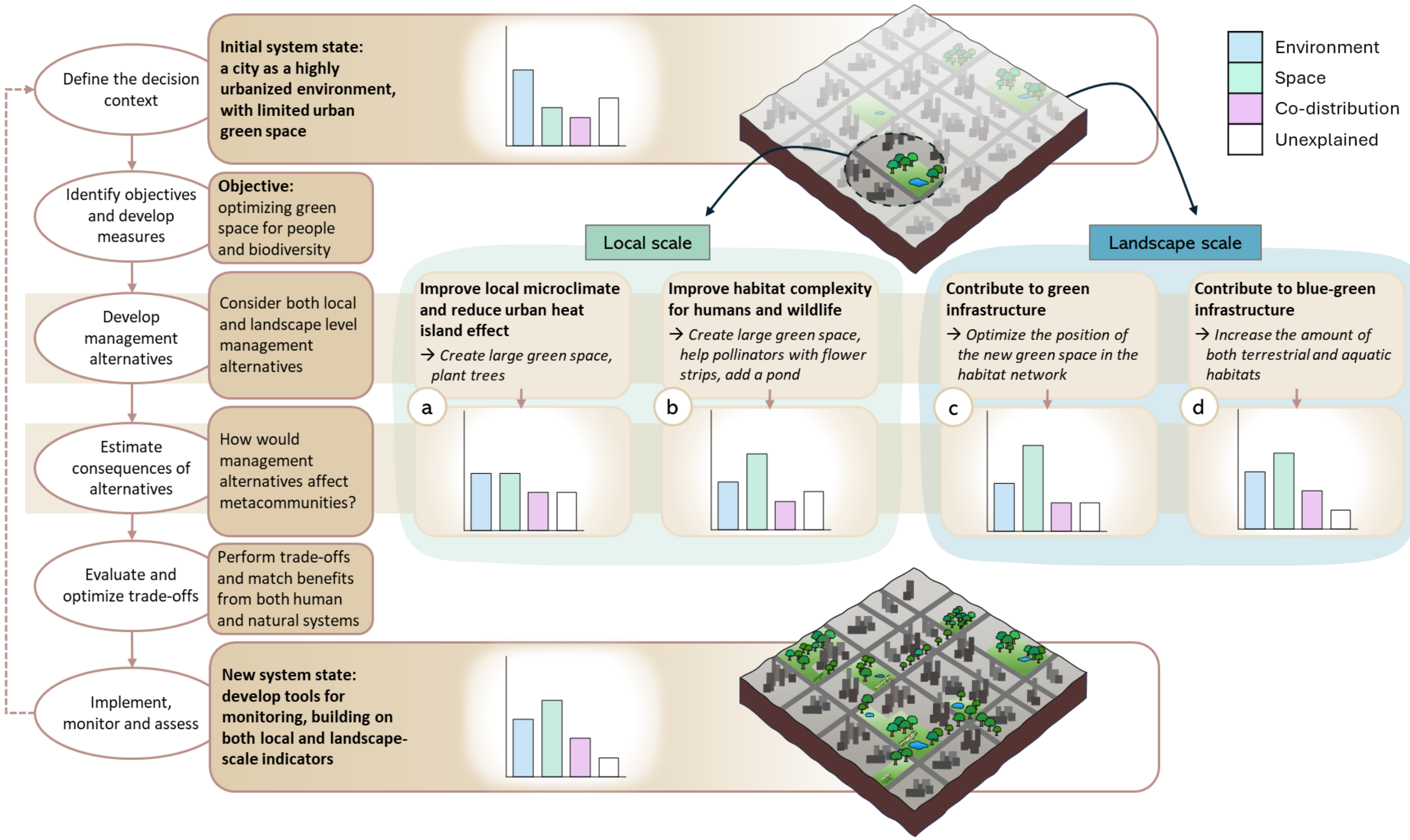

Figure S2: An example of a city aiming at optimizing green space for people and biodiversity, which, depending on the local (cases "a" and "b") or landscape perspective ("c" and "d"), might lead to different relative strengths of metacommunity processes (color coding follows **Figure 2** in the main text).

Text S2 Optimizing urban green spaces

Metacommunity processes in urban landscapes can be similarly constrained as in fragmented riverine systems. Remnants of natural habitats are often isolated in the urban matrix, limiting dispersal. Our example here is a city dominated by built-up surfaces and in need of more urban green space. While this need can be primarily human-driven (e.g. for recreation, well-being, or microclimate regulation), there is an increasing focus on optimizing the design of green space for both people and biodiversity. Although this holistic approach integrates multiple objectives, different management alternatives can still strongly influence the scale and the outcomes for metacommunities.

Focusing on local benefits often leads to prioritizing the size and complexity of individual green patches. This can still create functional habitats supporting multiple taxa and ecosystem services, for example, unmanaged lawns and flower strips benefit pollinators, while tree-lined streets provide shading and mitigate urban heat islands. While these features may incidentally improve connectivity within the urban matrix (reflected in cases “a” and “b” in **Figure S2**), a more explicit landscape perspective would also consider the spatial positioning of new green spaces (“c”). This might favor multiple smaller patches in a stepping-stone design or the addition of green corridors, which can even add further ecosystem services provided by urban green spaces. Additionally, enhancing overall urban blue-green connectivity may influence decision-making by increasing not only habitat, but also landscape complexity, introducing underrepresented microhabitats, or incorporating habitat types like urban ponds to strengthen ecological connectivity (“d”).

In both local and landscape-scale approaches, dispersal rates may increase - either as an incidental outcome of independent decisions or through explicit management aimed at connectivity. Locally optimized designs, such as larger green spaces with improved microclimate, may reduce abiotic stressors, weakening abiotic selection relative to initial conditions (“a” and “b” in **Figure S2**). Larger habitats may also reduce stochasticity linked to small population sizes, while increased habitat complexity can enhance resource availability and lessen biotic interactions among dominant species (“b” in **Figure S2**).

Landscape-scale interventions reshape metacommunity processes by increasing habitat number and spatial linkages, leading to greater dispersal opportunities and reduced stochasticity. Enhanced connectivity may lessen the dominance of random colonization events and buffer communities from environmental variability.

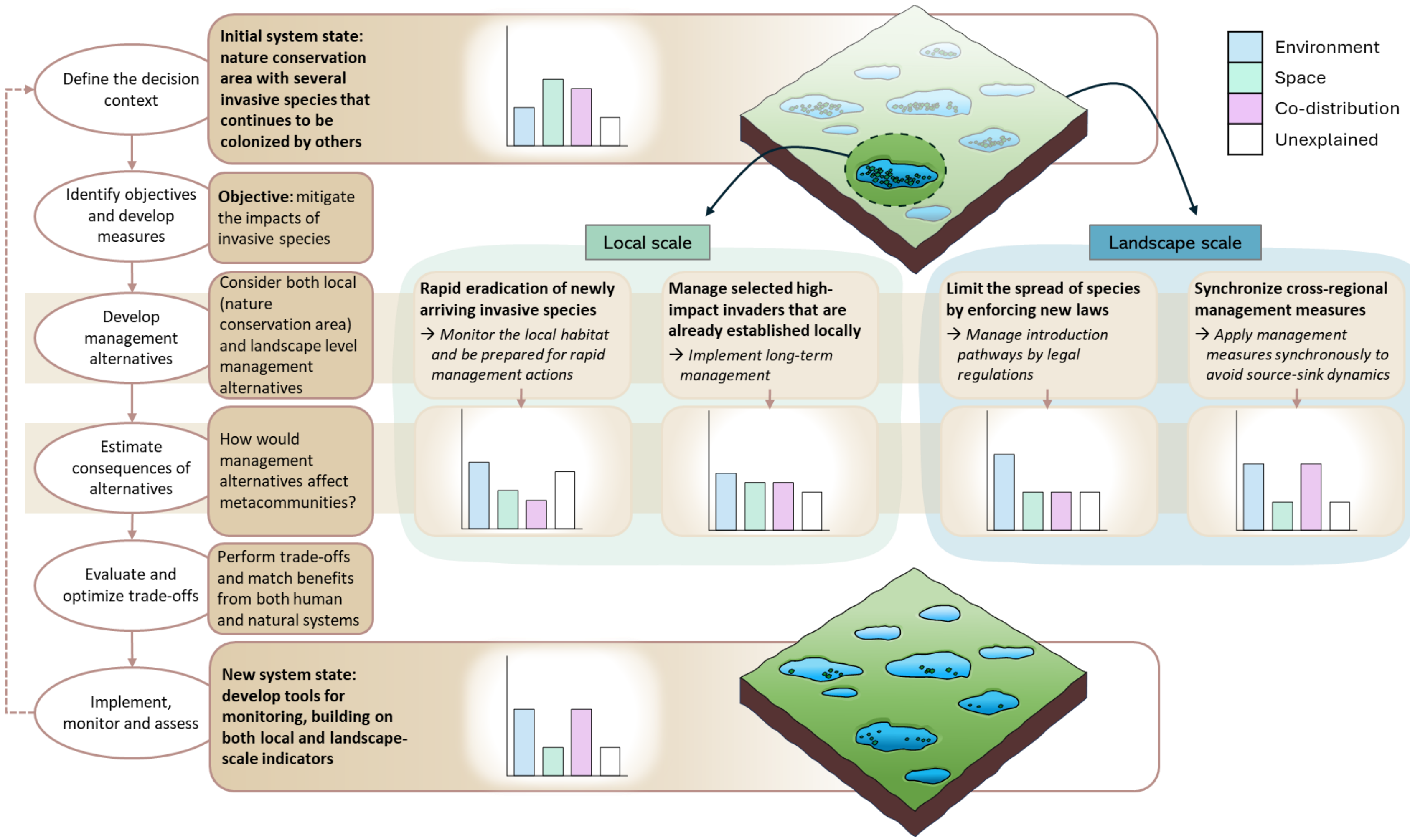

Figure S3: An example of a region (e.g., a nature reserve or national park) with several invasive species. To mitigate the negative impacts of invasive species on biodiversity and ecosystem services, management can concentrate on local (cases “a” and “b”) or landscape-level interventions (“c” and “d”) that might lead to different relative strengths of metacommunity processes (color coding follows **Figure 2** in the main text).

Text S3 Managing invasive species

The metacommunity context also provides a useful framework for understanding the spread and impacts of invasive species. For monitoring, modelling, and mitigating the spread of invasive species in a landscape, an explicit spatial context is necessary. This does not mean that at the local level, targeted management of high-impact invaders already arrived and established would not be imperative. Nonetheless, management interventions in, for example, a nature conservation area, can be more successful in the early phase of establishment (**Figure S3**, case "a"), whereas they become more costly and resource-intensive later, often needing repeated interventions to manage the local population of these species in the long term (cf. (Robertson *et al.* 2020; Sankaran *et al.* 2024). Overall, this may constrain regional-scale decision-making and result in focusing on a few high-impact invaders (case "b"). While these local actions might be successful at keeping things at bay, they are not sufficient to inhibit the spread of these species in a well-connected landscape, for which synchronized control would be necessary (case "d" in **Figure S3**). The introduction of a given species to new habitats can be strongly facilitated by human movement. Limiting the spread of these species by relevant laws can help decrease dispersal rates, thereby slowing their spread in the landscape (case "c"). Regarding these two landscape-level measures, one might draw parallels to the failure to globally control the recent COVID pandemic, where the absence of globally synchronized management ("d") and inconsistent lockdown measures ("c") similarly allowed rapid spread across regions (see also (Vilà *et al.* 2021) for parallels between epidemics and invasions).

As seen in three of the four cases, managing dispersal rates can be critical in the management of invasive species. At the same time, we can only expect long-term effects in cases "c" and "d" (landscape-scale measures), where dispersal rates of the invasive species would drop synchronously in the entire landscape as a result of a systematic intervention, inhibiting the movement of invasive species also over time. The quick local eradication of newly arrived species (case "a") can also have a similar effect (less realized dispersal), but it would only last as long as the necessary management steps are repeatedly carried out.

By eradicating invasive species (regardless of the local or spatial context), we can also expect the role of biotic selection to weaken, given that these species are usually quite strong players in their new communities. Hence, removing them from local habitats, or preventing their colonization, will lessen biotic selection and enable stronger abiotic selection, which are visible in all four cases to a certain extent. Alternatively, the relative influence of invasive versus native species on metacommunity processes can be explored more explicitly by partitioning analyses to contrast the drivers of invasive species occurrence against those shaping native community structure.

It is important to note that the mechanisms described here differ from management strategies that indirectly suppress invaders by modifying habitat conditions rather than by direct removal. For example, in the grassland case study (**Text S4** and **Figure 5** in the main text), reduced mowing intensity limits *J. aquatica* through enhanced competition and shading by resident vegetation. In such cases, the overall strength of biotic interactions among native species may increase even as the invader declines. Thus, the predicted direction of change in biotic selection depends on whether management acts through direct eradication (**Figure S3**) or through indirect, habitat-mediated processes that modify community assembly dynamics (**Figure 5** in the main text).

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Text S4 Analysis of the grassland management case study

This analysis illustrates how the Meta-CHANS framework can be applied to empirical data from a grassland management experiment in Central European wet meadows, aimed at controlling *Jacobaea aquatica*, a native species that has become locally overabundant due to changes in hydrological and management regimes (Krieger *et al.* 2022a, b). Three mowing intensities were compared: low (intensity 5-6; treatments V-1 and V-2), medium (intensity 15-16), and control, representing the original high intensity (intensity 28-36 in the original dataset). Data was used from low-productive and very low-productive sites. As some treatments were implemented intermittently (e.g. mowing every three years or following one- or two-year fallow periods), comparisons among management intensities were made for 2021, when treatment effects had time to become established.

Species abundance data were converted to presence-absence matrices, and species that were either singletons or ubiquitous were excluded. Environmental predictors included mean temperature and precipitation (three-month averages), altitude, pH, phosphorus, potassium, organic matter, total nitrogen, and C:N ratio, all scaled to zero mean and unit variance. Spatial coordinates were standardized.

Joint species distribution models (JSDMs) were fitted separately for each management intensity using the “sjSDM” package in R (Pichler & Hartig 2021; R Development Core Team 2012), with three predictor components: (1) environmental (abiotic), (2) spatial (dispersal), and (3) residual co-distributional (biotic). Model performance and variance partitioning were extracted using ANOVA and the function “internalStructure”. Results were visualized with barplots and ternary plots showing the relative contribution of these processes with the help of “ggplot” and “ggtern” (Hamilton & Ferry 2018; Wickham 2011).

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