

Meta-CHANS: Linking metacommunity ecology with decision-making

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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.

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Abstract

Ecological dynamics and the management of natural systems are both structured by local and larger regional spatial effects. In ecological dynamics, these are addressed by metacommunity ecology, but how multi-scale human management and policy interact with ecological dynamics is less well-developed. Here, we propose a unifying framework – Meta-CHANS – that integrates metacommunity ecology (Meta-) with Coupled Human And Natural Systems (CHANS) that links ecological dynamics with structured decision making and ecosystem services policymaking. Using conceptual examples, we show how local and landscape-level management choices can shift the relative importance of metacommunity processes, leading to different biodiversity and ecosystem outcomes. By explicitly linking ecological processes to decision-making, Meta-CHANS provides a framework for comparing management strategies and improving decision-relevant ecological predictions.

Linking spatial dynamics and human–nature systems

For millennia, humans have interacted with natural systems through diverse land-use practices, including indigenous and traditional land-use practices [1]. However, the intensity and spatial extent of human pressures have increased dramatically, and virtually no part of Earth is now free of human influence. Human activities are increasingly shaping ecosystems across spatial scales, creating complex feedback between ecological dynamics and decision-making. The concept of **Coupled Human And Natural Systems (CHANS; [2,3])** emphasizes these reciprocal links between humans and natural systems (see **Glossary**). The **metacommunity** concept similarly addresses how local and regional ecological dynamics (largely mediated by dispersal) reciprocally affect each other. The two systems share nonlinear relationships, adaptive components, feedback loops, and multi-scale structures in space and time, presenting a challenge for developing conceptual frameworks that can address these links in ways that support decision-making (**Figure 1**).

We propose that integrating a **meta-ecology** perspective [4] with CHANS [2,3] provides a framework for understanding these spatial interactions and supporting more effective conservation decisions. Below, we (a) outline key elements of CHANS and **structured decision-making**, and (b) integrate these with a metacommunity perspective into a new framework, Meta-CHANS. We (c) illustrate its application using conceptual examples. Finally, (d) using these examples, we highlight how shifting the scale (from local to regional) in management alternatives can modify spatial processes, with consequences for biodiversity, ecosystem properties, and **Nature’s Contributions to People (NCP)**.

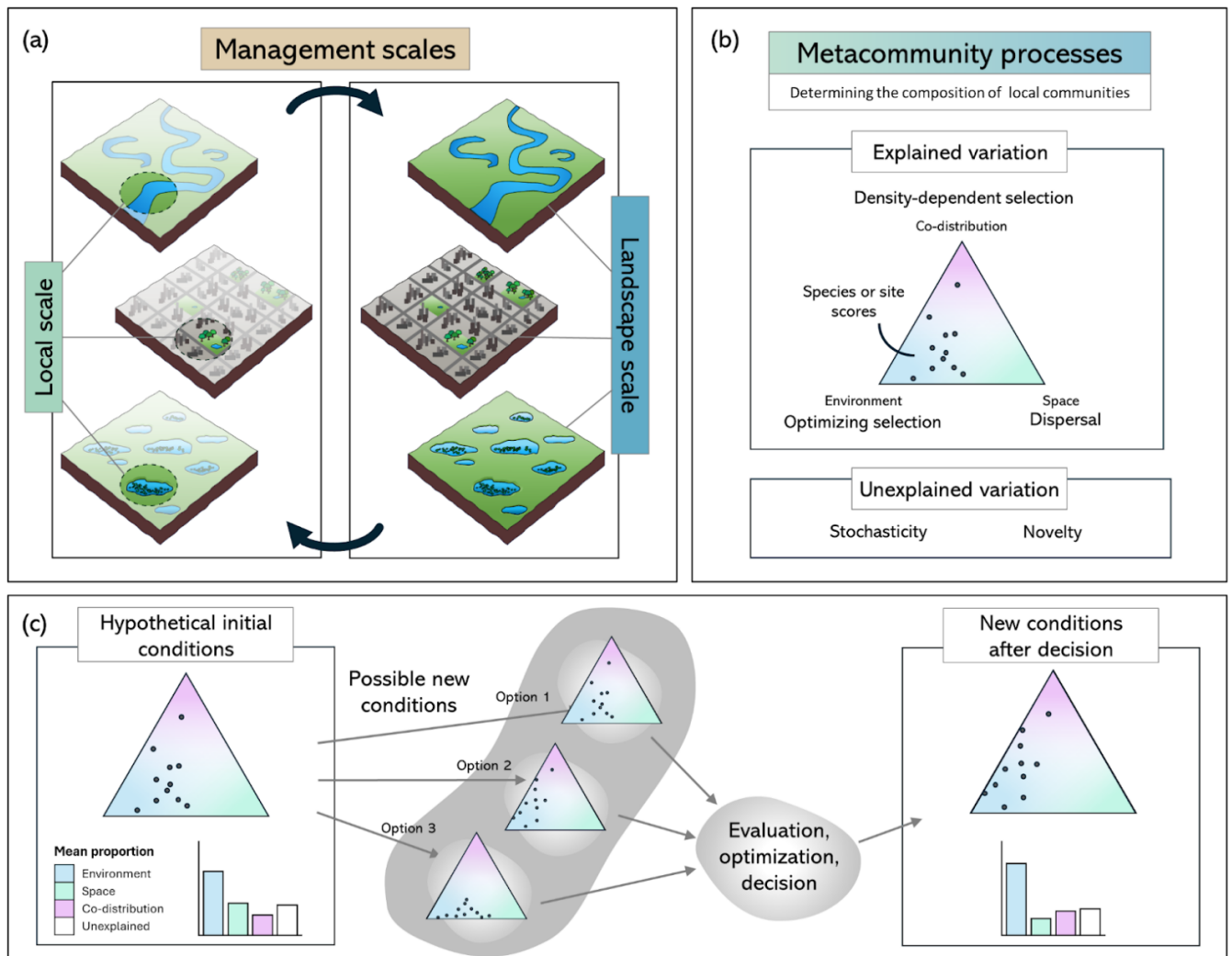


Figure 1 (a) Local- and landscape-scale processes jointly shape biodiversity and ecosystem dynamics. Local-scale management targets conditions within individual sites, while landscape-scale management can address spatial connectivity and cross-site interactions. **(b)** Metacommunity structure can be understood as the combined outcome of multiple ecological processes, which can be quantified using variation partitioning approaches (e.g., JSdMs; see Box 1). **(c)** Management decisions alter the relative importance of these processes, leading to alternative system states across spatial scales (illustrated schematically).

Structured decision-making and CHANS

At the practical level of environmental management, we draw on structured decision-making [5,6] which provides a transparent framework for comparing alternative management options under multiple objectives (**Figure 2a**). Structured decision-making integrates science-based evidence, stakeholder values, and formal decision-analytic tools to evaluate the expected consequences and relative utility of alternative actions. The framework emphasizes the balanced use of these choices through sequential steps. Although often implemented for specific management decisions at local or regional scales,

these decisions are embedded within broader policy, socio-economic, and temporal contexts [7]. We use the CHANS framework to represent this broader decision context (**Figure 2b**). In this view, management decisions are not isolated interventions, but components of coupled human and natural systems, in which social preferences, economic constraints, governance structures, and ecological feedback interact across scales. To capture how societal values enter this coupling, we connect structured decision-making with the ecosystem services and nature's contributions to people literatures [8–10] as well as with political theory [11]. In our framework, nature's contributions to people help define societal values and provide criteria for evaluating trade-offs among management alternatives (**Figure 2c**).

This creates a parallel structure between the ecological metacommunity and the human side of CHANS. In both cases, local, context-dependent dynamics (e.g., species interactions or management decisions) are shaped by broader regional contexts (e.g., species pools or policy frameworks). Conversely, these regional contexts can emerge from the cumulative effects of local processes and decisions.

Metacommunity dynamics across scales

Metacommunity ecology provides a process-based, spatially explicit framework for understanding how local communities are shaped by **abiotic** and **biotic selection, dispersal, stochasticity**, and **novelty** across landscapes. By explicitly linking local and regional dynamics, this perspective offers a natural bridge to CHANS, where decision-making similarly operates across spatial scales.

As a first approximation, several of the processes can be studied using **Joint Species Distribution Models (JSDMs; Box 1 and Figure 1b)**. These models provide a flexible framework to estimate environmental and spatial effects, quantify residual species co-distribution patterns, and partition variation in community composition into environmental, spatial, co-distribution, and unexplained components [12,13]. One key feature of JSDMs, that contrasts with previous approaches like variation partitioning of community data, is that they can be used to isolate the contributions of individual species and sites to overall metacommunity structure [12,14]. This enables the identification of species and localities that disproportionately influence observed metacommunity patterns (**Box 1**). Such insights can guide conservation and restoration efforts by linking community patterns to underlying processes and their responses to management.

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

We link ecological metacommunity dynamics with human activities by partitioning local and regional components of both (**Figure 2d**). **Metacommunity processes** connect local (green, left) and landscape-scale (blue, right) components of the natural system, and management actions at these scales therefore have both local and landscape-level ecosystem

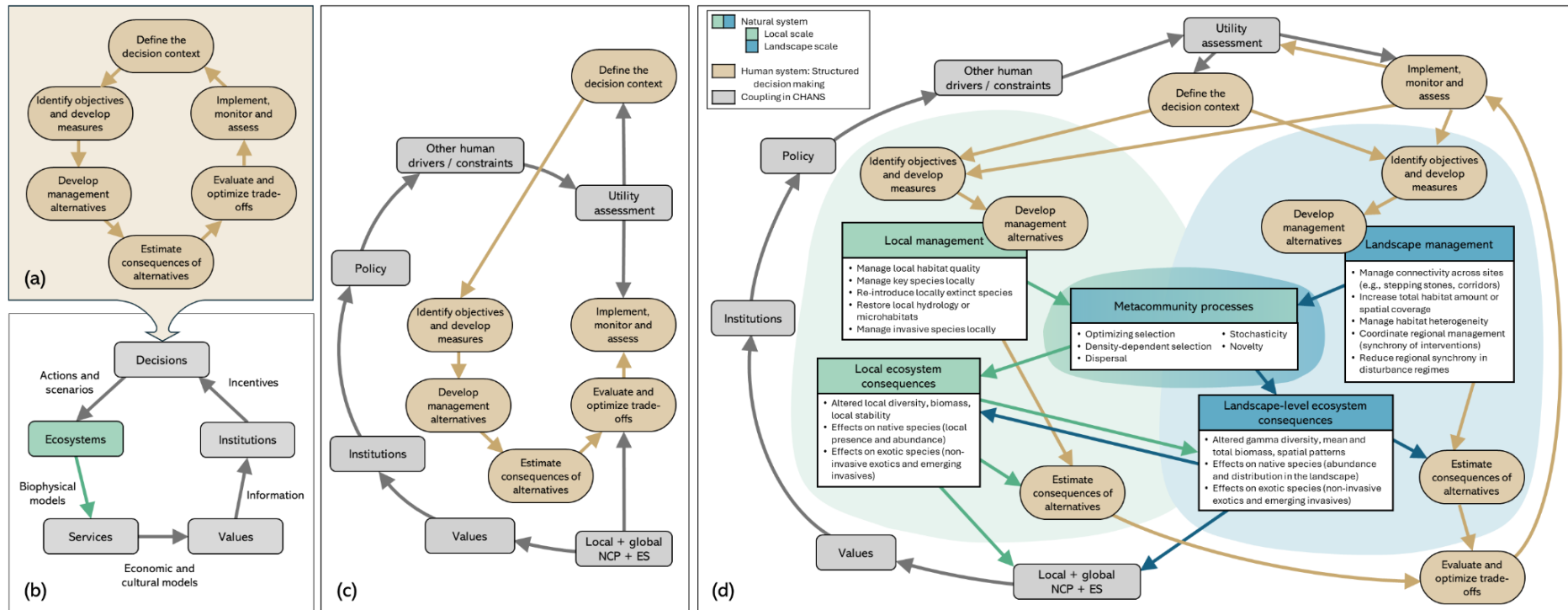


Figure 2 Direct integration of the sequential steps of structured decision-making **(a)** into the human system side of Coupled Human and Natural Systems (CHANS) **(b)**, including nature’s contributions to people (NCP) and ecosystem services (ES) at local and global scales **(c)**. This integration is further combined with metacommunity ecology to form the Meta-CHANS framework across local and landscape scales **(d)**. The framework links management actions, metacommunity processes, ecosystem consequences, utility assessment, and socio-economic feedbacks, illustrating how management actions influence metacommunity processes and ecosystem outcomes, which in turn influence decision-making through policy, institutions, and societal values.

consequences by altering the relative strength of these processes. A general decision-making scheme is integrated (brown) with a conceptual approach directed at policy-making [8], representing key socio-economic elements of the CHANS framework (gray).

Because of the strong reciprocal feedback between scales, the final elements of structured decision-making (optimization and implementation) are shared across scales, emphasizing that management options should be evaluated and coordinated jointly rather than in isolation. Resulting ecosystem consequences contribute to NCP and re-enter the decision-making cycle through evaluation and optimization.

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). This feedback can alter utility assessments and thereby influence future management priorities. Explicit attention to cross-scale interactions – such as enhancing connectivity, increasing habitat heterogeneity, or coordinating restoration across sites – creates opportunities to regulate metacommunity processes and improve both regional biodiversity and local ecosystem consequences.

Conceptual demonstration

To illustrate the application of the Meta-CHANS framework, we present three conceptual examples representing different management contexts (**Figure 3**). We describe one example in detail (urban green space planning) and use the others (river and invasive species management) to highlight the generality of the underlying mechanisms.

Urban landscapes (**Figure 3a**) provide an example of a CHANS context in which spatial structure, connectivity, and human decision-making are tightly coupled. Remnants or restoration of natural habitats are typically isolated within the urban matrix, limiting dispersal. There is increasing focus on optimizing green space design for both people and biodiversity, but different management alternatives can have contrasting effects on urban metacommunities. Focusing on local benefits often prioritizes the size and complexity of individual green spaces, creating functional habitats that support biodiversity and ecosystem services. While such designs may incidentally improve connectivity, a landscape perspective explicitly considers the spatial positioning of green spaces, for example through stepping-stone configurations or corridors that enhance connectivity and landscape heterogeneity, introducing underrepresented microhabitats, or incorporating habitat types like urban ponds.

At the landscape scale, the coordinated placement of green space reshapes metacommunity dynamics by directly increasing habitat number and connectivity. In an urban context, this means that decisions about where to locate new parks, corridors, or other blue-green elements affect not only local habitat quality but also colonization opportunities and metacommunity stability across the city. Compared with isolated local interventions, such designs can reduce the influence of stochastic colonization events, buffer communities against local disturbances, and promote spatial turnover rather than the biotic homogenization typically observed in highly urbanized landscapes [15,16]. Within the Meta-

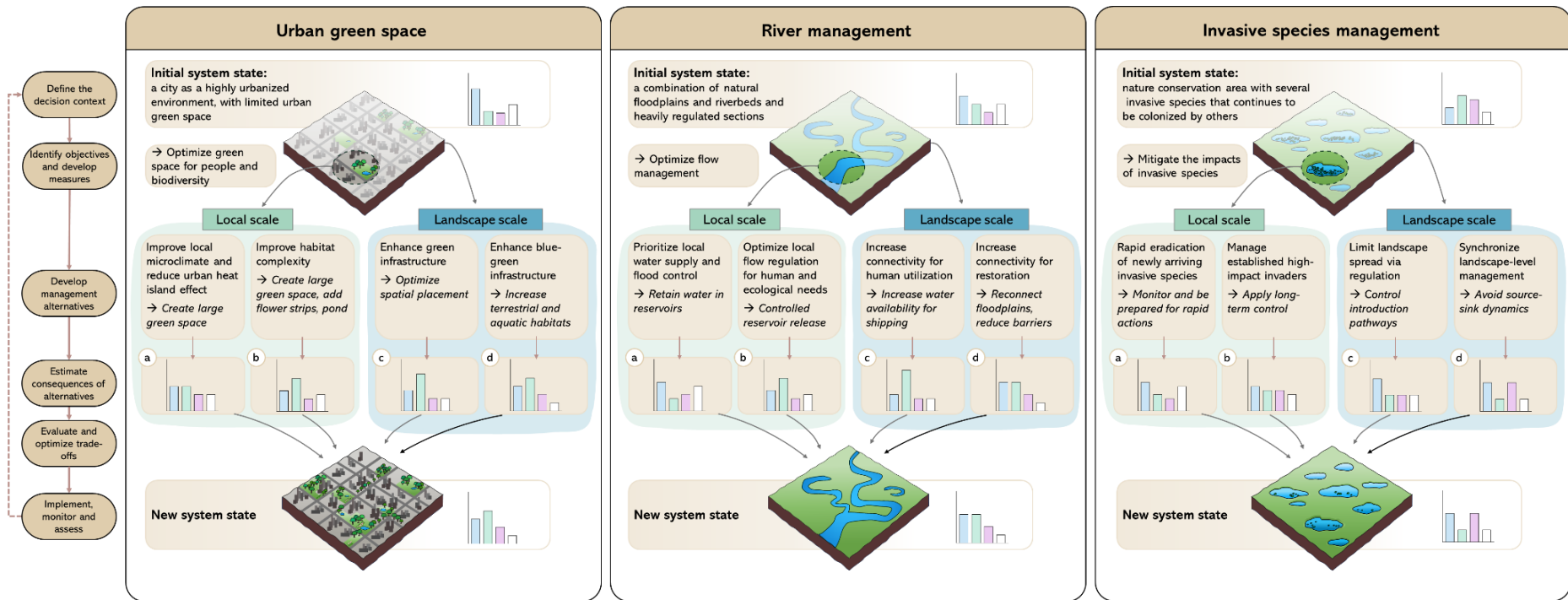


Figure 3 Conceptual examples illustrating how management at local (cases “a” and “b”) and landscape scales (“c” and “d”) can shift the relative contribution of metacommunity processes to community structure (illustrated by barplots; colour coding follows **Figure 1**). Differences among management alternatives reflect how decisions alter process strengths and resulting ecological outcomes.

CHANS framework, these projected changes in the relative strength of metacommunity processes provide a clear and decision-relevant basis for comparing alternative urban planning strategies.

Similar dynamics emerge in the other examples. In river networks, local interventions such as flow regulation or dam operation alter abiotic conditions and dispersal pathways, while landscape-scale measures targeting connectivity can reshape metacommunity dynamics across entire catchments (**Figure 3b**). In the context of invasive species, early local eradication can reduce establishment, but long-term control typically requires coordinated landscape-scale management that limits dispersal (**Figure 3c**). Across systems, the relative effectiveness of local versus landscape interventions depends on how management actions modify dispersal, environmental filtering, and cross-scale feedback.

Implications for conservation decision-making

Metacommunity ecology can be a powerful structural basis for integrating ecological processes with human activities by providing tools for understanding how biodiversity responds to anthropogenic stressors [17–19], or even conservation management [20–22]. Taking a metacommunity perspective can improve practical decision-making within structured decision-making frameworks [5]. Metacommunity approaches can be utilized to describe initial conditions in nature and then forecast the impact of alternative management actions at local and regional scales (**Figure 1c**). Recent advances importantly allow the identification of species or sites that contribute disproportionately to metacommunity structure (e.g., through unique environmental, spatial, or residual components in JSDMs; see **Box 1**), highlighting species or sites where local management is likely to have a strong influence on metacommunity dynamics, with effects extending beyond the managed site or species.

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

JSDMs extend Species Distribution Models (SDMs): while SDMs relate environmental and spatial factors to dispersal-driven 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 frameworks that differ in their technical approaches and are undergoing rapid development [13,30,42]. Here, we focus on their conceptual contribution to understanding metacommunity dynamics.

JSDMs provide two basic types of outputs [12,13]. First, they partition variation in community composition among environment (reflecting mostly abiotic factors), space (dispersal), residual co-distribution among species (potentially reflecting biotic interactions), and unexplained variation (including stochasticity and novelty; **Figure B1**). This partitioning can also be applied to individual species. These components can be visualized using ternary plots [14], where the position of species or sites can indicate 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 inform conservation management by identifying key drivers of focal species distributions (e.g., rare or invasive species). 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 to high stochasticity in species distributions. This can provide information for the prioritization of sites for biodiversity conservation.

Second, JSDMs estimate parameters that identify important environmental gradients, spatial scales, and shared species responses. These parameters provide additional insights into metacommunity structure and can guide management.

Interpretation of JSDMs has limitations. Unmeasured environmental variables and spatial processes can bias estimates of residual co-distribution and unexplained variation, and pattern-to-process inference remains sensitive to scale and model specification [29,43,44]. Nevertheless, JSDMs already provide multiple types of information relevant for conservation decision-making, and ongoing methodological developments, including advances in machine learning and artificial intelligence, are likely to enhance their utility further.

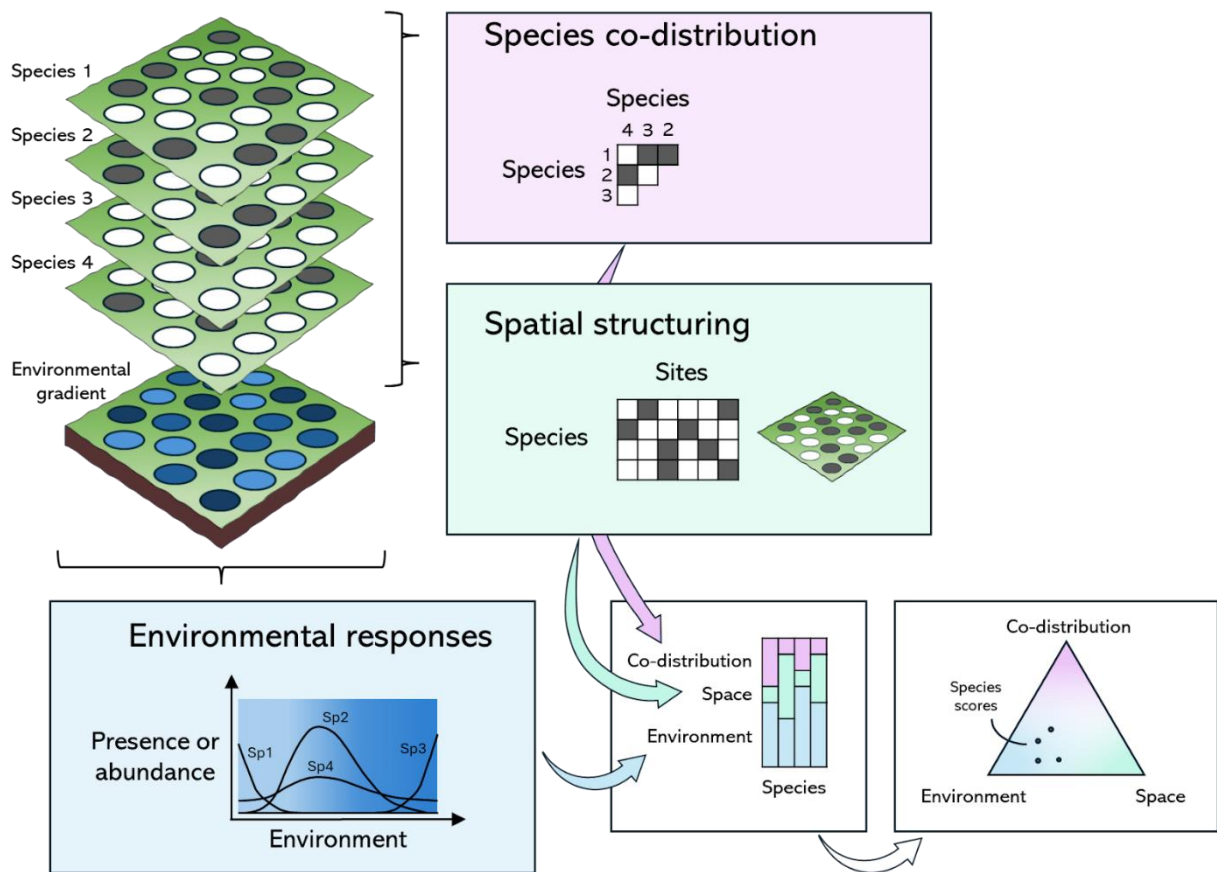


Figure B1 Decomposing metacommunity patterns into environmental, spatial, and co-distribution components using JSDMs, where residual variance represents unexplained variation, including stochasticity and unmeasured processes.

Within Meta-CHANS, ecosystem properties such as biodiversity, compositional stability, or spatial turnover are treated as emergent, decision-relevant outcomes, allowing management options to be compared based on expected ecological consequences. While the reliability of these projections depends on how well the pattern-to-process inference works, currently available tools already provide useful insights, and will likely continue to improve (**Box 1**). By exploring alternative management options and their projected impacts on landscape-level dynamics, this framework can support more informed decision-making by enabling prospective comparison of management scenarios within a structured decision-making context, rather than relying on retrospective before-after evaluations.

Socio-economic context and implementation

We place our proposed framework within a broader socio-economic and policy context that focuses on the enhancement of (ecosystem services and) NCP [8]. Regulations and incentives can modify the utility functions underlying management decisions, shaping how ecological and societal outcomes are balanced. While these utility functions are influenced by complex cultural and institutional factors beyond the scope of metacommunity ecology, ecological dynamics can still feed back to societal values, for example, by altering perceptions and valuation of biodiversity and ecosystem complexity. Although we adopt a simplified representation of these interactions, more detailed socio-economic frameworks [7,9,10,23,24] would likely lead to similar conclusions. While NCP occupies a key position in the framework we built, we chose to keep it simple and general 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.

Limitations and challenges

Applying the Meta-CHANS framework involves several challenges. One key issue is the potential mismatch between the spatial scales of metacommunity processes and those of decision-making. While we simplified the framework to two spatial levels, these do not necessarily correspond to governance scales. For example, regional ecological processes may interact with both local decision-making and broader policy contexts, and understanding these mismatches remains an important area for future work.

Recent methodological progress allows for the analysis of complex, species-rich communities, for example, through eDNA-based metabarcoding and AI [25–27], through which it is now possible to detect formerly unseen members of these communities, offering deeper resolutions of community patterns [28]. However, inferring processes from these patterns remains difficult [29], which is also critical for understanding the consequences of human activities. Powerful statistical tools such as JSDBMs (**Box 1**) and related methods [12–14,30] are improving our ability to analyse spatial community data, and future work is likely to further strengthen pattern-to-process inference [31–35]. At the same time, simpler metacommunity approaches, including multivariate analyses and variation partitioning [36–

38], remain useful when embedded in robust study designs such as before-after-control-impact comparisons.

Finally, Meta-CHANS should be viewed as a framework for identifying plausible ecological pathways rather than producing deterministic forecasts. Ecological responses can depart from theoretical expectations because of historical contingencies, species-specific traits, local environmental conditions, and complex feedback. Predictions based on metacommunity theory should therefore be treated as informed approximations that identify likely directions of change and key sources of uncertainty. The value of Meta-CHANS is to make assumptions explicit, compare alternative ecological pathways, and support adaptive management through iterative monitoring and revision.

Future directions and integration

The application of Meta-CHANS highlights the need for stronger integration between ecological and human systems. This will require interdisciplinary collaboration among ecologists, conservation practitioners, socio-economists, and policymakers, combining quantitative analyses with local knowledge and socio-economic considerations. 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 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 [39–41]. 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. Furthermore, traditional and indigenous land-use systems provide relevant empirical examples of long-term human-nature coupling in which spatially explicit decision-making (e.g., burning, harvesting, hunting) can generate fine-grained land-use mosaics with landscape-level ecological consequences. Within Meta-CHANS, such systems can empirically demonstrate how human decision-making can structure ecological processes and communities across spatial scales.

Concluding remarks

Strengthening our understanding of how nature and societal dynamics are coupled remains a major challenge. Here, we have focused on the multi-scale 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. Both ecological communities and societies 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.

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References

1. Ellis, E.C. *et al.* (2021) People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences* 118, e2023483118
2. Liu, J. *et al.* (2007) Coupled human and natural systems. *AMBIO: a journal of the human environment* 36, 639–649
3. Liu, J. *et al.* (2021) Coupled human and natural systems: The evolution and applications of an integrated framework: This article belongs to Ambio's 50th Anniversary Collection. Theme: Anthropocene. *Ambio* 50, 1778–1783
4. Schiesari, L. *et al.* (2019) Towards an applied metaecology. *Perspectives in ecology and conservation* 17, 172–181
5. Gregory, R. *et al.* (2012) *Structured decision making: a practical guide to environmental management choices*, John Wiley & Sons
6. Clemen, R.T. and Reilly, T. (1999) *Making hard decisions with DecisionTools Suite*, Duxbury

7. Díaz, S. *et al.* (2018) Assessing nature's contributions to people. *Science* 359, 270–272
8. Daily, G.C. *et al.* (2009) Ecosystem services in decision making: time to deliver. *Frontiers in Ecol & Environ* 7, 21–28
9. Mandle, L. *et al.* (2021) Increasing decision relevance of ecosystem service science. *Nature Sustainability* 4, 161–169
10. Xu, Z. and Peng, J. (2022) Ecosystem services-based decision-making: A bridge from science to practice. *Environmental Science & Policy* 135, 6–15
11. Ostrom, E. (2009) A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* 325, 419–422
12. Ovaskainen, O. *et al.* (2017) How to make more out of community data? A conceptual framework and its implementation as models and software. *Ecology Letters* 20, 561–576
13. Pichler, M. and Hartig, F. (2021) A new joint species distribution model for faster and more accurate inference of species associations from big community data. *Methods Ecol Evol* 12, 2159–2173
14. Leibold, M.A. *et al.* (2022) The internal structure of metacommunities. *Oikos* 2022
15. Lokatis, S. and Jeschke, J.M. (2022) Urban biotic homogenization: Approaches and knowledge gaps. *Ecological Applications* 32, e2703
16. McKinney, M.L. (2006) Urbanization as a major cause of biotic homogenization. *Biological Conservation* 127, 247–260
17. Gounand, I. *et al.* (2018) Meta-Ecosystems 2.0: Rooting the Theory into the Field. *Trends in Ecology & Evolution* 33, 36–46
18. McFadden, I.R. *et al.* (2023) Linking human impacts to community processes in terrestrial and freshwater ecosystems. *Ecology Letters* 26, 203–218
19. Simmons, B.I. *et al.* (2021) Refocusing multiple stressor research around the targets and scales of ecological impacts. *Nature Ecology & Evolution* 5, 1478–1489
20. Chase, J.M. *et al.* (2020) Biodiversity conservation through the lens of metacommunity ecology. *Annals of the New York Academy of Sciences* 1469, 86–104
21. Messenger, M.L. *et al.* (2023) A metasystem approach to designing environmental flows. *BioScience* 73, 643–662
22. Patrick, C.J. *et al.* (2021) The application of metacommunity theory to the management of riverine ecosystems. *WIREs Water* 8, e1557
23. Mace, G.M. (2014) Whose conservation? *Science* 345, 1558–1560
24. Soga, M. and Gaston, K.J. (2020) The ecology of human–nature interactions. *Proceedings of the Royal Society B: Biological Sciences* 287, 20191882
25. Fajgenblat, M. *et al.* (2025) Leveraging Massive Opportunistically Collected Datasets to Study Species Communities in Space and Time. *Ecology Letters* 28, e70094
26. Ruppert, K.M. *et al.* (2019) Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review in methods, monitoring, and applications of global eDNA. *Global Ecology and Conservation* 17, e00547
27. Waldock, C. *et al.* (2024) Deconstructing the geography of human impacts on species' natural distribution. *Nat Commun* 15, 8852
28. Hartig, F. *et al.* (2024) Novel community data in ecology-properties and prospects. *Trends in Ecology & Evolution* 39, 280–293
29. Blanchet, F.G. *et al.* (2020) Co-occurrence is not evidence of ecological interactions. *Ecology Letters* 23, 1050–1063

30. Ovaskainen, O. *et al.* (2025) Common to rare transfer learning (CORAL) enables inference and prediction for a quarter million rare Malagasy arthropods. *Nature Methods* 22, 2074–2082
31. Chang, C.-W. *et al.* (2021) Reconstructing large interaction networks from empirical time series data. *Ecology Letters* 24, 2763–2774
32. Guzman, L.M. *et al.* (2022) Accounting for temporal change in multiple biodiversity patterns improves the inference of metacommunity processes. *Ecology* 103, e3683
33. Huang, C.-L. *et al.* (2024) Integrating several analytical methods to assess strength of ecological processes behind metacommunity assembly. *Oikos* 2024, e10166
34. Leibold, M. *et al.* (2025) Linking Pattern to Process in Metacommunities: Challenges and Opportunities. at <<https://ecoevorxiv.org/repository/view/9021/>>
35. Thompson, P.L. *et al.* (2020) A process-based metacommunity framework linking local and regional scale community ecology. *Ecology Letters* 23, 1314–1329
36. Borcard, D. *et al.* (1992) Partialling out the Spatial Component of Ecological Variation. *Ecology* 73, 1045–1055
37. Peres-Neto, P.R. *et al.* (2006) Variation partitioning of species data matrices: estimation and comparison of fractions. *Ecology* 87, 2614–2625
38. Legendre, P. *et al.* (2012) Variation partitioning involving orthogonal spatial eigenfunction submodels. *Ecology* 93, 1234–1240
39. Bodin, Ö. and Tengö, M. (2012) Disentangling intangible social–ecological systems. *Global Environmental Change* 22, 430–439
40. Kluger, L.C. *et al.* (2020) Studying human–nature relationships through a network lens: A systematic review. *People and Nature* 2, 1100–1116
41. Rickowski, F.S. *et al.* (2026) A Systems Perspective: How Social–Ecological Networks Can Improve Our Understanding and Management of Biological Invasions. *BioScience* 76, 127–146
42. Rahman, A.U. *et al.* (2024) Accelerating joint species distribution modelling with Hmsc-HPC by GPU porting. *PLOS Computational Biology* 20, e1011914
43. Poggiato, G. *et al.* (2021) On the interpretations of joint modeling in community ecology. *Trends in Ecology & Evolution* 36, 391–401
44. Zurell, D. *et al.* (2018) Do joint species distribution models reliably detect interspecific interactions from co-occurrence data in homogenous environments? *Ecography* 41, 1812–1819
45. Vellend, M. (2010) Conceptual synthesis in community ecology. *The Quarterly review of biology* 85, 183–206
46. Leibold, M.A. *et al.* (2022) Evolution and community assembly across spatial scales. *Annual Review of Ecology, Evolution, and Systematics* 53, 299–326
47. Urban, M.C. *et al.* (2008) The evolutionary ecology of metacommunities. *Trends in Ecology & Evolution* 23, 311–317
48. Heger, T. *et al.* (2019) Towards an integrative, eco-evolutionary understanding of ecological novelty: Studying and communicating interlinked effects of global change. *BioScience* 69, 888–899

Glossary

Optimizing selection (abiotic selection)

Density-independent selection involving responses to local abiotic conditions, where species have intrinsic growth rates and carrying capacities determined primarily by environmental factors assumed to be independent of the biota (e.g., temperature, salinity, incoming light).

Density-dependent selection (biotic selection)

Density-dependent selection occurs when different species are favored depending on the presence or abundance of other species and feedback among their interactions, including direct and indirect interactions such as competition, predation, or mutualism.

Dispersal

The movement of individuals among localities. If dispersal is limited, some localities will not be occupied by all the appropriate species; if dispersal is high, species may persist in localities where they would otherwise be selected against due to a high level of immigration maintaining sink populations.

Metacommunity

A set of local communities connected by the dispersal of multiple potentially interacting species, whose dynamics are shaped by processes operating across spatial scales.

Metacommunity processes

The five primary processes determining community dynamics across landscapes: optimizing (abiotic) selection, density-dependent (biotic) selection, dispersal, stochasticity (drift), and novelty [35,45] (**Figure 1b**).

Meta-ecology

Meta-ecology, a collective term encompassing metapopulation, metacommunity, and meta-ecosystem ecology, explicitly accounts for spatial dynamics and landscape structure.

Novelty

Originally conceived primarily as speciation [45], but other processes can also be included here that change the nature of the regional biota, such as long-distance colonization, perhaps due to human activities leading to biological invasions or shifts in regional climate leading to the establishment of range-expanding species. To date, novelty has received much less attention in metacommunity ecology than the other four processes (but see [46,47]). However, given the accelerating pace of human-induced changes to ecosystems, it may become increasingly relevant (e.g., [48]).

Stochasticity (drift)

Processes that cannot be related to selection or dispersal, including the stochastic nature of demographic events (e.g., births, deaths), colonization history, and disturbances due to outside forces.

Joint Species Distribution Models (JSDMs)

Models that estimate species-specific environmental and spatial effects, quantify residual species co-distribution patterns, and partition variation in community composition into environmental, spatial, co-distribution, and unexplained components.

Nature's Contributions to People (NCP)

Ecosystem contributions, such as habitat creation and maintenance, regulation of water quality, learning and inspiration, or supporting identity, used to evaluate trade-offs in decision-making.

Structured decision-making

A framework integrating science-based approaches, consensus-based societal procedures,

and technocratic tools (e.g., multi-criteria evaluation) to evaluate management alternatives through sequential steps.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used AI to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.