Individual-based Ecology

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Forum Paper

The need for an individual-based global change ecology

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Abstract

Biodiversity loss and widespread ecosystem degradation are among the most pressing challenges of our time, requiring urgent action. Yet our understanding of their causes remains limited because prevailing ecological concepts and approaches often overlook the underlying complex interactions of individuals of the same or different species, interacting with each other and with their environment. We propose a paradigm shift in ecological science, moving from simplifying frameworks that use species, population or community averages to an integrative approach that recognizes individual organisms as fundamental agents of ecological change. The urgency of the biodiversity crisis requires such a paradigm shift to advance ecology towards a predictive science by elucidating the causal mechanisms linking individual variation and adaptive behaviour to emergent properties of populations, communities, ecosystems, and ecological interactions with human interventions. Recent advances in computational technologies, sensors, and analytical tools now offer unprecedented opportunities to overcome past challenges and lay the foundation for a truly integrated Individual-Based Global Change Ecology (IBGCE). Unravelling the potential role of individual variability in global change impact analyses will require a systematic combination of empirical, experimental and modelling studies across systems, while taking into account multiple drivers of global change and their interactions. Key priorities include refining theoretical frameworks, developing benchmark models and standardized toolsets, and systematically incorporating individual variation and adaptive behaviour into empirical field work, experiments and predictive models. The emerging synergies between individual-based modelling, big data approaches, and machine learning hold great promise for addressing the inherent complexity of ecosystems. Each step in the development of IBGCE must systematically balance the complexity of the individual perspective with parsimony, computational efficiency, and experimental feasibility. IBGCE aims to unravel and predict the dynamics of biodiversity in the Anthropocene through a comprehensive study of individual organisms, their variability and their interactions. It will provide a critical foundation for considering individual variation and behaviour for future conservation and sustainability management, taking into account individual-to-ecosystem pathways and feedbacks.

Key words: Agent-based, biodiversity crisis, climate change, ecological theory, individual trait variation, predictions, scaling up

Introduction

Ecosystems worldwide are undergoing unprecedented changes due to anthropogenic drivers. Climate change, habitat loss, overexploitation, pollution and invasive species are threatening biodiversity and ecosystem functioning, causing dynamic shifts at all levels and scales of ecological systems (Scheffers et al. 2016; Jaureguiberry et al. 2022; Peixoto et al. 2022). Local extinctions and invasions often trigger cascading effects that alter species communities and food webs, pushing entire ecosystems towards tipping points and irreversible change (Scheffer et al. 2001; Dakos et al. 2019). These biodiversity and ecosystem responses are difficult to anticipate and predict because the relevant drivers often act synergistically, pushing ecosystems out of equilibrium (e.g., rangeland degradation and desertification in drylands worldwide; Maestre et al. 2022). To make matters worse, changes in environmental conditions are highly stochastic and non-stationary, i.e. they vary in space and time, such as turbid and clear water conditions in shallow lakes (van der Bolt et al. 2018; Hastings et al. 2018; Shoemaker et al. 2020). In particular, transient dynamics in response to abrupt or ongoing anthropogenic change, which can last for decades or even centuries, are the norm rather than the exception under conditions of global change. One example is the ‘extinction debt’, where species loss continues long after habitat change (Krauss et al. 2010). Halting biodiversity loss and ecosystem degradation under continuing or even accelerating anthropogenic pressures will require novel approaches and concepts that improve our mechanistic and predictive understanding of the complex response of ecological systems and their components to environmental change (Urban et al. 2022; Cerini et al. 2023).

Current ecological theories and predictive models often rely on simplified descriptions of ecological systems based on aggregated units (e.g., populations, species, communities, or trophic levels) and assume equilibrium conditions. Although these simplifications increase the tractability of models, they limit a fully mechanistic and predictive understanding (Bolnick et al. 2011; Radchuk et al. 2014; Jeltsch et al. 2019; Cerini et al. 2023). Summary descriptions of process rates and equilibrium assumptions also limit the transferability of findings across time and space, and obscure the prediction of transient dynamics (Kleiven et al. 2018). In particular, when dynamics are based on non-linear processes (which is the norm in ecology), averaging assumptions lead to potentially erroneous conclusions. This fact is already described in Jensen’s inequality (‘the fallacy of the average’), which states that for non-linear functions, the system response to average conditions is different from the average response to variable conditions (Jensen 1906; Denny 2017).

A key example of the importance of individual variation in understanding the collective response of populations, communities and entire ecosystems to global change is dispersal. Dispersal drives invasion processes, range shifts, and the success of species establishment. Individual differences in dispersal ability, often linked to behavioural traits such as boldness (Dammhahn et al. 2020) or genetic differences, can influence the establishment success of invasive or colonising species, with only some specific phenotypes or genotypes allowing successful dispersal (Fig. 1, González-Suárez et al. 2015; Premier et al. 2020). Similarly, biodiversity responses to land-use change, landscape fragmentation, and habitat loss have recently been linked to individual-level variation in behavioural and other traits (Rohwäder and Jeltsch 2022; Szangolies et al. 2022, 2024; Wolfgang et al. 2023; Rohwäder et al. 2024).

Indeed, individual responses and individual variation play a pivotal role in almost all ecological processes, including not only priority effects and invasions (Premier et al. 2020; Ruland and Jeschke 2020), but also food-web dynamics (Gårdmark and Huss 2020; Ceulemans et al. 2021), extinction of (small) and genetically deprived populations (Jeltsch et al. 2019), predator-prey and host-pathogen dynamics (Scherer et al. 2020; Kürschner et al. 2021; Casanelles-Abella et al. 2023; Grabow et al. 2024), species range shifts (Valladares et al. 2014; Donelson et al. 2019), animal migration (Fandos et al. 2020), community assembly (Clark 2010; Violle et al. 2012; Schirmer et al. 2020; Leibold et al. 2022) and community stability (Barabas and d’Andrea 2016; Crawford et al. 2019), nutrient supply (Allgeier et al. 2020), formation of novel ecosystems (Heger et al. 2019; Schlägel et al. 2020) and provisioning of ecosystem services (e.g., in the context of fisheries, Monk et al. 2021).

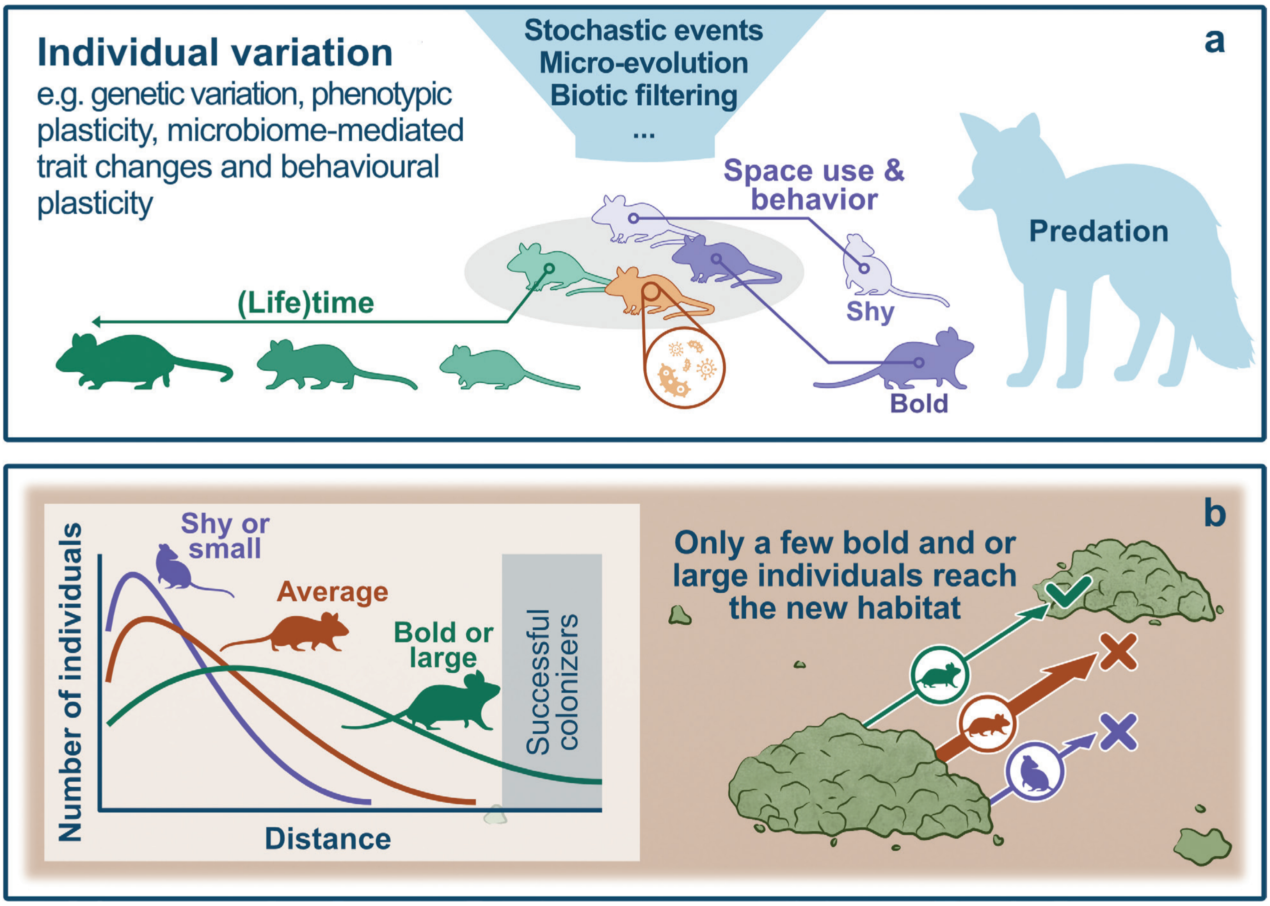

Figure 1. Examples of individual variation and its consequences: **a** individual variation describes the variation in traits, including behaviour, between or within individuals resulting from various processes such as microevolution and biotic filtering. It also explicitly includes variation induced by experience, health status or microbes and microbial communities associated with the host. The example visualises a mammal, but the processes are relevant to all organisms; **b** simplified example showing how successful colonisation or invasion depends on inter-individual variation in morphological or behavioural traits (González-Suárez et al. 2015; Dammhahn et al. 2020; Premier et al. 2020).

The above examples highlight the growing evidence for the critical role of individual variation and adaptive behaviour in shaping complex ecological dynamics. However, few studies have causally linked individual variation to complex biodiversity dynamics and ecosystem functioning (Wolf and Weissing 2012; Crawford et al. 2021). While individual-based concepts have been developed in theoretical ecology (e.g. Grimm and Railsback 2013), these approaches have largely been limited to modelling single species or simplified modules of pairwise interactions, with a few exceptions such as forest gap models (Grimm 1999; DeAngelis and Grimm 2014; DeAngelis 2018, see also a companion paper on individual-based ecology by Grimm et al. 2025, this issue).

Two main challenges have hindered the development of a truly integrated individual-based ecology (IBE) (for definition of IBE see Box 1, and for more details on IBE see the related companion paper by Grimm et al. 2025, this issue): First, difficulties in collecting and handling individual-specific data, and second, insufficient computational power. Even disciplines such as behavioural ecology, plant ecology and evolutionary biology, where inter-individual differences and genetic and phenotypic variation have been extensively documented (e.g., Hellweger et al. 2016; Kindermann et al. 2022; Laskowski et al. 2022; Schmitz

Box 1. Individual-based ecology (IBE).

IBE aims to understand population, community and ecosystem dynamics arising from the variation among individual organisms, their response to, and variable interactions with, the biotic and abiotic environment. This approach is applicable to all forms of life, from bacteria to plants, fungi, invertebrates and vertebrates, to reveal emergent eco-evolutionary phenomena and feedbacks across different levels of organisation. While individuals in many macrobial species are relatively easy to identify, distinguishing individuals in modular macrobes, such as filamentous fungi and clonal plants, or in microbial species, is more challenging but increasingly feasible.

et al. 2024), have rarely explored their consequences for more complex processes and higher ecological levels. Research in these disciplines often remains focused on single species or pairwise interactions as the primary unit of analysis (Terhorst et al. 2018). A deeper understanding of eco-evolutionary feedbacks within communities and ecological networks requires the integration of community ecology with evolutionary biology. Such a synthesis would reveal how genetic and phenotypic variation among individuals, as well as evolutionary processes within a species, can shape the ecological properties of communities and ecosystems (De Meester et al. 2019).

The time is ripe to live up to previous claims and move ecology towards a predictive science (Mouquet et al. 2015; Elliott-Graves 2019; Johnston 2024). For global change scenarios, there is a strong need to systematically explore the causal mechanisms linking individual variation to emergent properties in multi-species communities and ecosystems. Achieving this ambitious goal will require a shift in ecological science from the simplifying, averaging view of early ecology to an individual-based ecology of global change – a science that explicitly recognizes individuals as fundamental agents of ecological and evolutionary change (see Box 2).

Box 2. Individual-Based Global Change Ecology (IBGCE).

IBGCE aims to capture, understand and predict the emergent response of ecological systems to key drivers of global change using individual-based ecological approaches (Box 1).

Taking full account of the role of individual variation, this framework assesses the impact of key anthropogenic drivers of global change on ecological and evolutionary dynamics. The IBGCE approach places particular emphasis on resilience, non-linear transitions and emergent properties of ecosystems, functions and services.

Why now?

Recent massive advances in technology and analytical tools enable IBGCE through new high-resolution data collections on a much larger scale, for multiple species and different taxonomic groups and ecosystems. For example, novel sensors that allow high-resolution monitoring of the physiology and behaviour of interacting individuals (e.g., high-throughput animal tracking systems, Nathan et al. 2022; Roeleke et al. 2022), multi-omics and (meta-) barcoding approaches to identify intraspecific and cryptic diversity (Schmitz et al. 2024) and to assess the distribution of community traits (Clark et al. 2023), as well as in situ animal personality tests, advanced remote observations (including the remote detection of unique patterns of individual organisms, Clapham et al. 2022), and meso- and microcosm experiments of experimental evolution (e.g. Agha et al. 2018; Mazza et al. 2020; Lustenhouwer et al) will play a key role in providing an empirical foundation for IBGCE. Machine learning and other advanced analytical approaches now provide the ability to process and interpret 'big' datasets, linking data from large numbers of interacting individuals with high-resolution environmental data and system-level information (Heppenstall et al. 2021; Nathan et al. 2022; Wiegand et al. 2025). These advances can provide the basis for refining existing concepts and developing new theories, and offer unprecedented insights into the underlying dynamics that structure ecological systems through the lens of individual organisms. Systematic recognition of the importance of individual variation, plastic behavioural responses or rapidly evolving behaviours in ecological systems will transform our fundamental understanding of how biodiversity and its components emerge from individual responses and interactions, and how the emerging levels of organisation will respond to changing environments (Fig. 2). Much-needed future scenario analyses and predictions, as a critical basis for management and mitigation, run the risk of being short-sighted and potentially biased if they ignore individual responses and rapid adaptations of organisms and the cascading eco-evolutionary processes that shape communities.

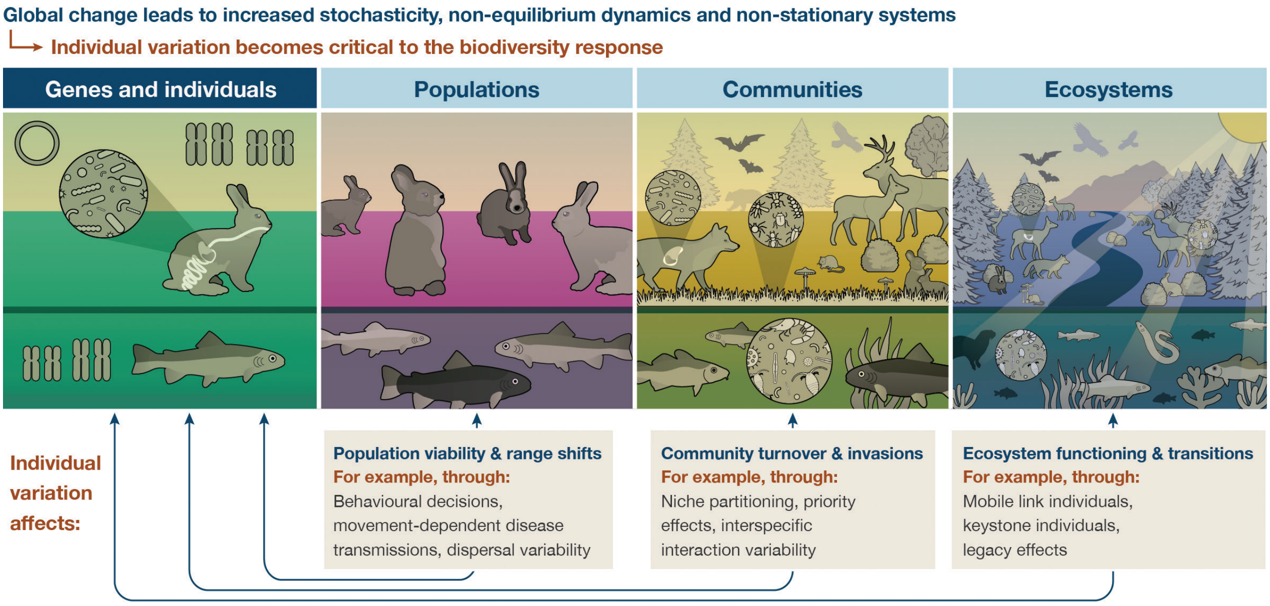

Figure 2. Hierarchical organisation from genes to ecosystems. Individuals are the elementary particles of ecological systems, meaning that variation and interactions between individuals can scale up to emergent properties at the population, community and ecosystem levels. The different ecological levels are highly interconnected through both bottom-up and top-down processes. Elucidating these feedback loops through an individual-based lens is a prerequisite for understanding ecosystem resilience and response to global change.

The road ahead

Unravelling and predicting biodiversity dynamics in the Anthropocene, taking into account the individuality of organisms, their variability, and ecological interactions, requires an empirical-experimental and conceptual foundation based on comparable data analyses, experiments and modelling approaches across species groups and systems to identify overarching principles and develop a synthesis theory. Extensive field and experimental work on trait variation, for example in movement and decision making in animals or in functional traits in plants or microbial communities, coupled with data science approaches, have already allowed the development and testing of new hypotheses on emergent phenomena and provided first insights into their underlying mechanisms (e.g. Bolius et al. 2020; Ceulemans et al. 2021; Vanvelk et al. 2021; Wesener et al. 2021; Eccard et al. 2022; Stiegler et al. 2022). Consequently, an important next step will be to systematically investigate how individual-level variation translates into community and ecosystem-level processes across organisational, taxonomic and ecological scales, and across different ecosystems (Fig. 2). For example, the study of emergent properties at different levels of organisation for different taxonomic groups should consider the co-evolution and network formation of communities (from microbes to top predators in terrestrial and aquatic systems), the formation and dynamics of metapopulations and metacommunities, and the relationships between biodiversity and ecosystem functioning.

Building on a causal, individual-based understanding of the driving mechanisms underlying ecological and evolutionary dynamics, an important step of IBGCE will be to further explore the role of individual variability in mediating ecological responses to global change drivers and improving mechanistic predictions of biodiversity changes (Grimm et al. 2017; Railsback et al. 2020; Musters et al. 2023). While a growing number of studies highlight the potential role of individual variation in global change impact analyses, systematic empirical, experimental and modelling studies across ecosystems that consider multiple global change drivers and their characteristics (e.g. gradual or abrupt, predictable or stochastic) are still largely lacking. In addition, a more systematic consideration of individual variability in predictive modelling remains to be achieved (Musters et al. 2023), in particular with a focus on transient eco-evolutionary dynamics under global change and the (mediating or cascading) effects of individual variation on them.

While predictive modelling is crucial for assessing future impacts of global change, a shift towards IBGCE also requires a solid theoretical and methodological foundation (Grimm et al. 2024). This includes the systematic testing and adaptation of prevailing ecological theories and concepts to the IBGCE paradigm. Recent examples include the integration of individual-based concepts from movement ecology into broader biodiversity theory (Schlägel et al. 2020), the integration of eco-evolutionary dynamics into community assembly (De Meester et al. 2016), the refinement of foraging theory to include adaptive behaviour (Railsback 2022), or the extension of modern coexistence theory by the complementary concept of coviability (Jeltsch et al. 2019). Recent research has also significantly advanced the field by highlighting the importance of individual variation for understanding community dynamics and biodiversity conservation (Merrick and Koprowski 2017; Crawford et al. 2021; Rohwäder and Jeltsch 2022; Eccard et al. 2022; Rohwäder et al. 2024; Szangolies et al. 2024), which is particularly important for non-equilibrium and non-stationary conditions associated with global change (Jeltsch et al. 2019; Schlägel et al. 2020; Zurell et al. 2022).

Future theory and method refinement will clearly benefit from benchmark models and a common toolset to advance individual-based theory and cross-fertilise with whole-system experiments (e.g., Radinger et al. 2023) and empirical studies (Berger et al. 2024). Recent predictive tools include a generic platform for individual-based eco-evolutionary modelling (Malchow et al. 2021), statistical frameworks for estimating dispersal from heterogeneous and biased data (Fandos et al. 2023), accounting for phenotypic variation in dispersal to determine ecological dynamics during range shifts (Urban et al. 2022; Zurell et al. 2022; Eccard et al. 2023), and inferring species interactions from individual movement data (Schlägel et al. 2019). New advances in integrating individual-based modelling with big data approaches will facilitate wider use of complex model-data fusion (Malchow et al. 2024), and deep and machine learning approaches will facilitate data acquisition and complex analysis (Ryo and Rillig 2017; Fuller et al. 2020; Heppenstall et al. 2021; Ryo et al. 2021). An important next step will be to systematically address issues of necessary model complexity vs. parsimony. This will include considerations of computational efficiency and providing efficient solutions for synergistic combinations of individual-based approaches with more aggregating numerical and analytical methods (Fahse et al. 1998; Radchuk et al. 2016; Wiegand et al. 2021). Promising approaches include adiabatic approximations (Fahse et al. 1998), a well-established method in physics for studying self-organisation in systems. It allows quantitative assessments of how individual-level parameters and dynamics affect aggregated population-level parameters, which can be used to explore community dynamics (e.g. Wiegand et al. 2021, 2025). Alternatively, model surrogates can be generated by genetic algorithms that evolve simplified, robust rules for individual decision making that can reproduce observed spatial and temporal patterns ('reinforcement learning', Fuller et al. 2020; An et al. 2021). Such patterns can be uncovered by machine learning techniques, including neural networks and deep learning (Heppenstall et al. 2021). In any case, the question remains whether model parsimony should be the central consideration, or whether the accuracy of predictions (capturing key patterns) overrides parsimony?

Finally, it will be crucial to better understand how we can manage individual variation and behaviour for conservation and sustainable management, taking into account individual-to-ecosystem pathways and feedbacks. A better understanding of the feedbacks between individual variation and ecosystem management will help to refine existing approaches to biodiversity conservation and management of ecosystem services, which still largely focus on populations, communities or other aggregated measures at the ecosystem or landscape level. Currently, individual variation is rarely explicitly considered in conservation and management decisions (DeAngelis et al. 2021), and research on how these decisions affect system stability is largely lacking (but see Wachter et al. 2023; Hajiesmaeili et al. 2024). Implicitly, however, this variability is highly relevant to stakeholders, biodiversity conservation and ecosystem services. For example, large-scale harvest experiments coupled with high-resolution monitoring have shown how populations and ecosystem functions and services respond to trait-selective fishing (Monk et al. 2021; Sbragaglia et al. 2022), and how changes in behavioural traits can feed back to limit catchability, harvest and monitoring (Arlinghaus et al. 2017). Initial model-based results also highlight the importance of accounting for differences in animal behaviour in biodiversity conservation (Andersen et al. 2018; Rohwäder and Jeltsch 2022; Szangolies et al. 2022; Rohwäder et al. 2024), particularly in reintroductions with limited numbers of released individuals (Premier et al. 2020). It will be important to extend such research to a wide range of ecosystems and taxonomic groups to gain general insights and understand the feedbacks between individual variability and ecosystem services and management.

In the long term, the new individual-based perspective should also be applied to outreach activities, for example in museums and schools. For example, the emerging individual-based perspective in the IBGCE data, models and simulations can make an important contribution to interactive educational multimedia that can be used for inquiry-based learning approaches (de Jong 2006) and data-driven dialogue formats that involve the wider public in the process of acquiring knowledge and help to raise awareness of the societal value of science (Nisbet and Scheufele 2009).

Conclusion

Individual-Based Global Change Ecology (IBGCE) offers a transformative framework for addressing the challenges of biodiversity loss and ecosystem degradation in the Anthropocene. By explicitly focusing on individual variation and its mediating role, IBGCE complements traditional ecological research. It also has the potential to unite diverse research fields by linking ecology and evolution, aquatic and terrestrial systems, micro- and macroscales, and urban and rural landscapes (see Grimm et al. 2025, this issue). This integrative approach can elucidate the underlying structure of ecological systems and the forces that govern them, from individual adaptation to population maintenance, community assembly and ecosystem functioning. Focusing on multiple (possibly interacting) drivers of global change, IBGCE research will need to combine empirical studies, ex- and in-situ experiments, novel eco-informatics approaches, advanced metadata analysis, artificial intelligence and deep learning, and analytical, numerical and agent-based modelling. By synthesising knowledge across systems and scales, IBGCE will foster novel theory development and provide a unique basis for predicting the impacts of global change on biodiversity and ecosystem functioning across scales. A causal understanding of the mechanisms underlying eco-evolutionary dynamics and the role of individual variation in these processes will offer a new foundation for adaptive and sustainable management in the context of non-equilibrium and non-stationary environmental conditions.

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Additional information

Conflict of interest

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Data availability

All of the data that support the findings of this study are available in the main text.

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