Individual-based Ecology

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Concepts and Synthesis

A manifesto for Individual-based Ecology

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Abstract

Ecology traditionally has been fragmented into separate branches that emphasise different localities, ecosystems, habitats, levels of organisation, applications, etc., and that use distinct terminologies and methods. Individual-based ecology (IBE) can unify these branches. By taking into account the variation, behaviours, and interactions of individual organisms, IBE links the responses of organisms to the responses of ecological systems: if we understand enough about individuals, we can predict complex system dynamics, even under novel conditions. But we must also consider the system level to know what characteristics of individuals are important. In IBE, both individual and system levels are considered simultaneously, either by collecting data at both levels or at least by linking data observed at one level to existing patterns or theories at the other level. Through this comprehensive perspective, IBE unifies the many separate branches of ecology. Methodological and conceptual advances already developed in the 21st century allow us both to make observations at both individual and system levels and to link them using individual-based models. These advances are transforming IBE from a vision into a feasible and necessary approach that makes ecology fit for addressing the shifts and challenges of the future.

Key words: Environmental change, individual-based ecology, novel conditions, paradigm, predictions, unification

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Introduction

Ecology was originally defined by Ernst Haeckel (1866) as the “science of the organism’s relationship to the surrounding world, where we can include all ‘conditions of existence’ in the broader sense. These are partly organic and partly inorganic in nature.” (p.286, original in German). In practice, however, ecology overlaps with many disciplines, including biology, chemistry, physics, geography, and soil science, and it has all kinds of more or less isolated branches. There are many “ecologies” (Table 1), none of which is exclusive. Rather, these ecologies reflect different emphases, such as localities (e.g. geographic; rural vs. urban), ecosystems (tropical, temperate), levels of organisation (population, community, ecosystem), processes (physical, physiological, behavioural), scales (microsite, landscape, continental), or applications (basic research, conservation, restoration). This separation of ecology into its many subdisciplines, often with their own terminologies, methods, journals, and even textbooks, has frequently been lamented; e.g., Huston et al. (1988) said "Each level of organization has traditionally been a separate field (e.g., physiological ecology, behavioural ecology, autecology, population ecology, community ecology, and ecosystem ecology). Each field has its own set of phenomena to explain…".

Table 1. A non-exclusive list of "ecologies"; there are many more (see also Anderson et al. 2021).

Landscape Ecology	Systems Ecology	Conservation Ecology	Restoration Ecology
Marine Ecology	Community Ecology	Plant Ecology	Physiological Ecology
Animal Ecology	Population Ecology	Tropical Ecology	Theoretical Ecology
Forest Ecology	Soil Ecology	Ecosystem Ecology	Global Ecology
Aquatic Ecology	Microbial Ecology	Behavioural Ecology	Desert Ecology

The fragmentation of ecology makes it difficult to identify, understand, and (critically) compare general mechanisms underlying the structure and dynamics of ecological systems. The different perspectives of the ecologies in Table 1 provide only partial insights and rarely a complete picture of all relevant factors, scales, and mechanisms (cf. Anderson et al. 2021). Even ecologies focussing on specific types of ecosystems, such as desert or forest ecology, which in principle are more holistic, are in practice split into branches focussing on, e.g. productivity, biodiversity, or management. The different scales, processes, and levels of organisation are all important for theoretical understanding and practical application, but traditional ecology provides little ability to link them. Even when we know that physiology or behaviour have important effects on population dynamics, how do we study and model those effects?

As an answer, we here present the case for Individual-based Ecology (IBE). We present a manifesto (Box 1), focussing on what IBE is and its conceptual background. In the following sections we summarize what IBE is and how it addresses these problems, then discuss why the potential for IBE to address

Box 1. The manifesto for IBE in a nutshell.

Manifesto for Individual-based Ecology (IBE)

- IBE is ecology that includes the individual-level perspective.
- IBE is needed to reliably predict the response of ecosystems to new conditions because individual-level mechanisms are more consistent and predictable than the system-level responses that emerge from them.
- IBE captures the inseparable link between the micro and macro levels of ecosystems.
- IBE is no longer a vision but has become feasible due to 21st-century advances in collecting, analysing, and modelling observations that include intra-specific trait variation, adaptive behaviour, and local interactions.
- IBE can transform and unify previously separate branches of ecology by providing a common framework for understanding system dynamics as emerging from individual characteristics and behaviour.

novel and dynamic conditions is especially important, and how IBE has become more feasible. In a companion article, Jeltsch et al. (2025) focus on the main motivation of IBE at these times: global change and the 21st-century advancements of ecology that make IBE possible.

Individual-based Ecology (IBE)

Individual-based Ecology (IBE) is an emerging paradigm (Jeltsch et al. 2025), which is not only essential in itself but also has the potential to unite the different branches of ecology. It takes into account the variation, behaviour, and interactions of individual organisms and how they affect, and are affected by, system-level dynamics. IBE is thus ecology that includes the individual-level perspective. So far ecology has focussed either on the system level or, in behavioural or evolutionary ecology, on the individual level, but IBE links both. In IBE, we study ecological systems as emerging from what explicit individuals do, and we study individuals to understand their characteristics that are important to system levels, i.e. populations, communities and ecosystems. This linkage is crucial because it is the properties and behaviours of the building blocks of ecological systems, the individual organisms, that determine the properties and behaviours of the systems they compose, and vice versa. A further crucial advantage of IBE is that it is "scale-explicit" (Meyer et al. 2010; Johnston 2024). Specifically, it explicitly reflects the awareness that ecological processes and patterns occur at different scales and levels of organization. Scale-explicitness helps to untangle the many different processes that happen in an ecosystem.

Throughout the history of ecology, the individual-based perspective has largely been avoided because explicitly considering individuals and what they do has seemed unnecessary or too difficult. To make conventional mathematics tractable, ecological modelling has either ignored individuals altogether, as in ecosystem ecology, or considered average individuals who are all the same, have no ontogeny, and interact globally in a homogeneous and constant environment. Similarly, empirical ecology has focused on highly aggregated variables such as mean trait values, abundance, species richness, or primary productivity; when individuals are considered, their variation and behaviour are rarely related to system-level dynamics.

Beyond equilibria

The traditional notion of a balance of nature (Pimm 1986) or, more generally, the concept equilibria, is obsolete. It never fully captured the dynamic nature of ecological systems but still was useful when quasi-equilibria or slow and thus negligible changes could be assumed. However, the environmental and social drivers of ecosystems, in particular anthropogenic climate change, human population growth, and the ongoing loss of biodiversity, require new approaches and concepts. Ecology needs to be relevant to solving real problems, in a changing world where all problems involve new conditions. Because our world is changing rapidly, predicting and managing ecological responses is especially important but especially difficult because we can no longer assume that systems will continue to behave as they have in the past. We need models and theories that are reliable under new conditions. System-level theory is not reliable under new conditions because formulating and solving system-level models requires simplifying away "details" that are often very important for predicting the responses to change. Moreover, such models require empirical parameters that can only be estimated from past observations and so are of questionable reliability under new or otherwise shifting conditions. The most reliable theory we have is that individuals act (and evolve traits) to increase their fitness, i.e. Darwin's theory of natural selection. Individual-based Ecology (IBE) is a way to use that theory to address system-level problems (Grimm and Railsback 2005).

IBE provides two capabilities that ecology can no longer go without: a framework for understanding realistic natural complexity and the ability to predict the response of ecological systems to novel conditions. For decades, ecological research has revealed the extent to which the need of traditional approaches to simplify away complexities has limited their usefulness for understanding and prediction. Prominent examples include scale-dependence and other ecosystem complexities examined by O'Neill (1986) and effects of risk avoidance behaviour on trophic dynamics as explored theoretically by Abrams (1993) and documented empirically by many studies (e.g., Preisser and Bolnick 2005). Thinking about and projecting ecological dynamics from the individual perspective is a natural and productive way to understand such complexities. Further, models driven by individual-level processes such as physiology and behaviour—which are more consistent and much easier to measure than ecological dynamics—seem much more reliable for predicting responses to new conditions under which empirical observations are impossible.

Still, while the vision of an IBE has long existed (Uchmański 1985; Huston et al. 1988), it did not previously seem possible, or necessary, to explicitly consider the variation, behaviour, and interactions of individuals to understand and predict the dynamics of ecological systems. This has changed in the 21st century. Moreover, these earlier visions of an IBE were based on a new kind of model, individual-based models, but experience since then has shown that we need not just a new kind of model but also new ways of doing empirical and theoretical ecology; and that new technologies were needed to make IBE feasible.

IBE has become feasible

The feasibility of both the empirical and modelling components of IBE have recently increased dramatically (Jeltsch et al. 2025). Collecting and analysing data on trait variation, behaviour, and local interactions of individuals has become practical at scales not previously imaginable. For many species we can now track movement across heterogeneous landscapes, study behaviour in natural environments, construct individual habitat suitability maps, use genetic markers to identify individuals and relatedness, etc. (Jeltsch et al. 2025). The growing recognition of the importance of individuals in understanding ecological systems has also led to long-term monitoring data, requiring a commitment and vision that had long been lacking. For example, determining the species, location, and size of every individual tree above a certain minimum size on a 50-hectare plot only began in 1985 and has since been repeated six times every five years, resulting in data on more than half a million trees (Condit et al. 2019). Also, the increasingly established FAIR principles (Findability, Accessibility, Interoperability, and the Reuse of digital assets) for making data robustly machine-actionable (Wilkinson et al.

2016) and the growing proficiency of ecologists in data science and AI (Artificial Intelligence) enable IBE by helping turn “big data” into useful knowledge.

While these new observation capabilities have many other uses in ecology, they contribute to IBE by making it more feasible to understand individual variation, identify patterns that characterise relations between individuals and systems (Grimm et al. 2005), and collect data to parameterize and calibrate complex bottom-up models.

Like empirical methods, use of individual-based models (IBMs, also referred to as agent-based models) has matured in the 21st century. Increasing computing power is often cited as the reason IBMs are much more commonly used, but methodological advances are also responsible. Specialized software platforms make IBMs much more accessible. Widely used protocols for communicating IBMs make these models transparent and reproducible, while standards for Good Modelling Practice are increasingly used (Grimm et al. 2014; Vincenot 2018). While early IBMs focussed on intraspecific trait variation (ITV) and often imposed demographic rates, advanced IBMs now include adaptive behaviour and local interactions and let, e.g., demographic rates emerge from the individuals’ behaviour and interactions. For this, the representation of behaviour is based on first principles such as energy budgets and fitness seeking (Grimm and Berger 2016; Szangolies et al. 2024). Especially important is the strategy of “pattern-oriented modelling”, which captures the whole rationale of IBE in a framework for learning how patterns observed at the macro and micro-levels of ecological systems are inseparably linked (Grimm et al. 2005; Gallagher et al. 2021).

These advances in empirical, including experimental, ecology, data analysis, and modelling complement each other. Building and analysing IBMs is a productive way to transform information, patterns, and relations observed under a broad range of conditions into knowledge and theory about the underlying processes. Still, while IBE has become possible, its implementation certainly can be challenging. It often will require collaboration across different disciplines and also various ecologies, for example in teams comprising experts in physiology, landscape and movement ecology, remote sensing, data science, and modelling. With IBE, ecology more often than not will have to become “big science”.

Discussion

Of course, emphasising the need for IBE does not mean that other “ecologies” are obsolete. IBE provides a unifying perspective both across ecologies (Grimm et al. 2017) and with other disciplines of biology. Instead of the traditional assumptions that systems can be understood without considering individuals, or that individuals can be understood without considering the systems they belong to, ecological research should assume by default that systems and individuals affect each other.

We are not the first to call for IBE, although that term seems to have been used first (others have used it since 2005) by Grimm and Railsback (2005). Łomnicki (1988) entitled his book “Population Ecology of Individuals”, while Walter and Hengeveld (2000) described an “ecology of organisms that is essentially an ongoing matching of their species-specific characteristics to the prevailing environmental factors and dynamics” (p. 15). There have also always been ecologists who, because of their own experience, emphasized the role of, e.g., intraspecific trait variation (ITV): "In nature ... behaviour that deviates from the norm or the assertiveness of 'lone wolves' can be decisive for the survival of the population." (Tischler (1979), p. 314, original in German). More recently, Musters et al. (2023) called for an "organism-based approach" to ecology, claiming that "better predictions can be made by focusing on organisms rather than species, because organisms are the primary biotic agents in ecosystems that respond directly to changes in their environment" (p. 1). Although they use a different term, "organism-based", they provide the key argument for why now is not only the opportune moment when IBE has become possible but also when we need it more than ever.

Conclusions

Our manifesto (Box 1) is a quest for the recognition of the importance of IBE as the basis for a predictive ecology of global change. Ideally, all the branches of ecology listed in Table 1 and beyond would be transformed by the individual-based perspective. At the same time, this manifesto also lays the foundation for this new journal "Individual-based Ecology"; we intend the journal to show how the individual-based perspective, in empirical, theoretical, and computational studies, benefits all branches of ecology.

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Additional information

Conflict of interest

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Author contributions

VG wrote the first draft, all authors revised and edited the manuscript through several iterations.

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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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